Theoretical Prediction of the Occurrence of Gas Hydrate Stability Zones: A Case Study of the Mohe Basin, Northeast China

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ABSTRACT: Source rocks of the Mohe Basin, Northeast China are gas-prone and the organic matter has advanced to late oil-generation stages, producing condensate and natural gas. This provides suitable conditions for the Mohe Basin to become one of the most prolific terrestrial natural gas hydrate (NGH)-bearing areas in China. Knowing this, here we predict the depth and thickness of pure methane hydrate stability zones (HSZs) and gas hydrate stability zones (GHSZs) via simulating the hydrate-phase equilibrium and other formation P−T conditions. Furthermore, factors that have a major impact on the occurrence of HSZs are discussed. Results showed that the composition of gas (guest) molecules and the geothermal gradient are the two most controlling factors on HSZs. Moreover, it was found that a pure methane HSZ with a thickness of about 255 m can form in areas with a geothermal gradient of <1.5 °C/100 m, with top and bottom depth limits less than 493 m and greater than 748 m, respectively. In contrast, pure methane hydrates have difficulty forming, while hydrates from wet gas can form where there is a geothermal gradient of >1.6 °C/100 m. Furthermore, a wet gas HSZ with a thickness of at least 735 m can be expected when the geothermal gradient reaches 2.3 °C/100 m, with top and bottom depth limits at 115 and 850 m, respectively. Ultimately, a pure methane HSZ can still form in the abnormally high-pressured areas when the geothermal gradient is up to 2.0 °C/100 m. Overall, HSZs can occur due to the combined effect of formation temperature, pressure, and gas composition. Finally, based on the results from this study and drilling data, future successful hydrate drilling schemes can be implemented in the Mohe Basin and similar terrestrial areas.

INTRODUCTION

Natural gas hydrates (NGH) are ice-like compounds that form when gas as the guest molecule is trapped within crystallized water molecules at a low temperature and a high pressure.1,2 NGHs can be divided into nonhydrocarbon and hydrocarbon gas hydrates based on the differences in the composition of the guest molecules. Among them, hydrocarbon gas hydrates can be further divided into pure methane and natural gas hydrates if heavier gas compounds constitute the guest molecules in the latter case. In general, pure methane hydrates are white and gradually become light yellow with as the content of heavier molecular compounds of the gas increases.3 In comparison to pure methane, heavier hydrocarbon gas molecules are more likely to form more stable hydrates under the same temperature−pressure conditions due to larger molecular diameters, weaker activities, and low diffusion coefficients.3,4

Hydrates are mainly formed in submarine slope zones and onshore permafrost regions under natural conditions.5−7 They have attracted global research attention since they bear massive natural gas resources and may cause global warming or induce geologic disasters after decomposition.8 At present, hydrate resources have mainly been discovered in the permafrost regions in the Wester Siberian Plain in Russian, the Oman Sea of the Iranian offshore, the Alaska North Slope in the United States, the Mackenzie Delta in Canada, and the Qilian Mountains in China.9−11

In recent years, the Chinese government has strategically strengthened the support for the research of hydrate resources from a clean energy utilization perspective. As a result, hydrates have become one of the nonconventional energy resources comparable to coalbed methane, shale gas, and shale oil.12 Recently, a significant breakthrough was made in the NGH production test project in the Shenhua Area, South China Sea, which was initiated by the China Geological Survey, the Ministry of Land and Resources of China.13,14 This marks the first successful attempt to produce combustible ice in China. The Mohe Basin, which hosts a major area of high-latitude and low-elevation permafrost, is located to the north of the Greater Hinggan Mountains in China and has also been proven to have great resource potential.15 Since 2010, scientific drilling of MK-1, MK-2, and many shallow wells has been
carried out in the Mohe Basin to prove the resource availability in the region. Zhang et al. have carried out a 1:50,000 geochemical survey of gas hydrate resources in areas with relatively developed frozen soil in the Mohe Basin, which serve as a major reference for understanding the migration, origin, and source of hydrocarbon gas in the deep undergrounds of the Mohe Basin and even as a guideline for the exploration of gas hydrates in this region.

Although the Mohe Basin is one of the most prolific areas in terms of gas hydrate accumulations, to date studies that report the distribution characteristics and governing factors of hydrate stable zones (HSZs) in the basin are rare and limited in scope. This is mainly due to the delay in the initiation of research on onshore hydrates in China, the complex geological background and evolution history of such basins (here the Mohe), and attempts to avoid wildfires in the frosted areas of the basin.

Considering the knowledge gap in the amount of gas hydrates in the Mohe Basin, this study attempts to delineate areas of HSZs that occur in the Mohe Basin based on the following factors: existing geothermal conditions of the Mohe Basin and its surroundings and the temperature−pressure equation of the hydrate-phase equilibrium. We have laid out criteria for the selection of prolific hydrate areas and depth intervals. Results from this study enable us to design exploratory wells in proper locations and also can assist the future analysis and reserve estimation attempts of favorable enriched hydrate resources around the globe.

**GEOLOGICAL SETTING**

**Basic Geological Setting.** The Mohe Basin is located in the most northern part of Heilongjiang Province, China, with geographic coordinates of 121°07′−125°45′ E and 52°00′−54°00′ N in an area of about 2.5×10⁴ km² (Figure 1). In terms of structural geology, it falls in the Erguna microplate in the Mongolia–Okhotsk fold belt. The Erguna microplate is adjacent to the Siberian Plate in the north and west, borders the Breya microplate in the east, and reaches the north end of the Da Hinggan Mountains in the south. Therefore, it lays in the collision and suture part between the Siberian Plate and a series of microcontinental blocks in Northeast China.

The basement rocks of the Mohe Basin consist of Precambrian granites or Pre-Triassic crystalline metamorphic rocks upon which the following formations are deposited from bottom to top: the Tongxiufeng, Ershierzhan, Mohe, and Kaikukang formations of the Upper Jurassic; the Tamulangou, Shangkuli, and Yiliekede formations of the Cretaceous; and the Tertiary Jinshan Formation (Figure 2). The strata in the basin feature a notable dual structure, i.e., the clastic sedimentary rocks that were dominant in the Upper Jurassic and the volcanic rocks that were mainly developed in the Cretaceous strata (Table 1).

The Mohe Basin can be divided into five second-order tectonic units: the Luoguhe depression, the Amuer depression, the Yaozhan depression, the Ershierzhan uplift, and the Emuerhe nappe zone. Volcanic rocks in the basin are generally distributed in the areas to the south of 53° N, which include the Tuqiang depression, the south end of the Changying fault depression, and the Mengkeshan depression. In comparison, sedimentary rocks are generally distributed in the Emuerhe nappe zone, the Ershierzhan uplift, and the north end of the Changying fault depression. The sedimentary rock strata suffered from uplifting and denudation due to activities of thrust nappes. As a result, the Xiufeng, Ershierzhan, and Mohe formations were successively exposed from the southeast to the northwest in the Emuerhe nappe zone. Meanwhile, microfractures are abundant in the strata, and the Mohe Formation along the banks of the Heilongjiang River experienced epimetamorphism.

**Frozen Soil in the Mohe Basin.** The frozen soil in Northeast China is dominated by the superimposed permafrost that formed during the ice age at the end of the Late Pleistocene and in the Late Holocene about 3000−12000 years ago. It can be divided into the following three types based on the degree of lateral continuity:

1. **Permafrost regions,**
where the frozen soil is transversely connected without discontinuities; (2) island-like thawing areas, where frozen soil is intermittently distributed in the transverse direction and disappears locally in the form of islands; and (3) island-like permafrost regions of frozen soil, where frozen soil is only distributed in the form of islands locally without transverse continuity. The Mohe Basin mostly lays in permafrost regions, with only a small part in the east laying in the island-like thawing areas of frozen soil.

The thickness of the frozen soil in the Mohe Basin greatly varies. According to public data, it has depths of about 75–100, 30–40, and 10–20 m in the basin center, mountain slopes, and mountain ridges, respectively, with a maximum thickness of up to 120 m near Jintao Town. Moreover, based on the interpretation of electrical prospecting data, the

| System     | Formation | Member | Thickness | Lithology                                                                 |
|------------|-----------|--------|-----------|---------------------------------------------------------------------------|
| Cenozoic   | Jilin     |        | 0-45      |                                                                           |
|            |           |        | 0-89      |                                                                           |
|             | Yiliehe   | Upper  | 0-596     |                                                                           |
|             |           | Lower  | 0-839     |                                                                           |
|             | Shangkuli | Upper  | 400-1656  | Fossils of bivalves, conchostracans, and plants                          |
|             |           | Lower  | 113-729   |                                                                           |
|             | Tamulangou|        | 0-1161    |                                                                           |
|             | Kaikuang  |        | 0-2734    | Bearing plant fossils                                                    |
|             | Mehe      |        | 1946-3980 | Fossils of gastropods, ostracods, plants, and sporopollen                |
|             | Ershierzhan|       | 800-4401  | Fossils of bivalves, ostracods, plants, and sporopollen                  |
|             |           |        |           | Fossils of plants, and sporopollen                                        |
| Basement    |           |        | 837-2806  |                                                                           |

**Figure 2.** Stratigraphic profile of the Mohe Basin.
thickness of the frozen soil is mainly 30–60 m within the scope of the 122°00′–122°25′ E and 53°20′–53°28′ N area of the Mohe Basin, with minimum and maximum values of about 20 and 150 m, respectively. Furthermore, the interpreted results also revealed that there is a mirror-image relationship between the top depth of the frozen soil and the elevation of the terrain. To be more specific, the frozen soil is thin and deeply buried at higher altitudes but thick and shallow at lower elevations.

**Gas Sources in the Mohe Basin.** Mudstones in the Upper Jurassic Ershierzhan and Mohe formations are abundant in organic matter, with average TOCs (total organic carbons) of 0.64% and 1.05%, respectively. Therefore, they are the most favorable source rocks in the permafrost regions in the Mohe Basin. Organic matter in the mudstones originated primarily from terrestrial higher plants and partially from lower aquatic organisms. Furthermore, organic petrology showed that the organic material mainly consists of type III kerogen with lesser amounts of types II and I, mainly producing natural gas from terrestrial higher plants and partially from lower aquatic organisms. Furthermore, organic petrology showed that the organic material mainly consists of type III kerogen with lesser amounts of types II and I, mainly producing natural gas from terrestrial higher plants and partially from lower aquatic organisms. Moreover, suitable conditions for biogas formation are also present in microfractured sections in the Quaternary and Upper Jurassic formations in the basin. An oxygen consumption zone of micro-organisms with a thickness of about 10 cm exists at the top of the Quaternary formation, which gradually becomes a reduction environment toward the deeper parts. This is favorable for anaerobic methanogens to produce biomethane and thus is the primary source of biogas production. The microfractured zones of the Upper Jurassic are up to 1600 m thick, which is favorable for the permeation of bacteria carried by atmospheric precipitation. Thus, the bacteria consume existing thermogenic hydrocarbons as nutritional substrates and produce a secondary biogas. Petrographic studies have shown that chloroform bitumen “A” in the source rock samples collected at a depth of less than 460 m contains significant amounts of non-hydrocarbons and asphaltene. Meanwhile, the aliphatic hydrocarbons in the samples generally show swelling phenomena in the gas chromatography studies, and norhopane series 17α(H) and 1β1(H)-25 were detected in the samples. All these infer that the residual aliphatic hydrocarbons in the source rocks may have suffered from biodegradation. Moreover, the core-adsorbed gas contains a certain amount of olefin, and its δ13C1 is between −79‰ and −64‰, revealing biogas genesis. All these suggest the abundance of gas sources in the area, which means that the occurrence of prolific areas or zones favorable for the development of NGHs depends on the occurrence of hydrate stable zones that are concurrently controlled by temperature and pressure.

### Table 1. Occurrence Characteristics of Pure Methane Hydrate Stability Zones under Different Formation Temperatures in the Mohe Basin and Normal Pressure Conditions

| geothermal gradient (°C/m) | frozen soil thickness (m) | burial depth of top boundary (m) | burial depth of bottom boundary (m) | thickness (m) | geothermal gradient (°C/m) | frozen soil thickness (m) | burial depth of top boundary (m) | burial depth of bottom boundary (m) | thickness (m) |
|---------------------------|--------------------------|--------------------------------|-----------------------------------|-------------|---------------------------|--------------------------|--------------------------------|-----------------------------------|-------------|
| 1.0                       | 10                       | 402                            | 1587                              | 1185        | 1.4                       | 60                       | 530                            | 782                              | 252         |
|                           | 30                       | 389                            | 1624                              | 1235        |                           | 100                      | 435                            | 924                              | 489         |
|                           | 60                       | 370                            | 1676                              | 1306        |                           | 120                      | 405                            | 978                              | 573         |
|                           | 100                      | 348                            | 1745                              | 1397        |                           | 150                      | 369                            | 1049                             | 680         |
|                           | 120                      | 337                            | 1778                              | 1441        |                           | 150                      | 369                            | 1049                             | 680         |
|                           | 150                      | 323                            | 1827                              | 1504        |                           | 150                      | 369                            | 1049                             | 680         |
| 1.2                       | 10                       | 480                            | 1076                              | 596         |                           | 10                       | 10                             | 60                               | 10          |
|                           | 30                       | 452                            | 1127                              | 675         |                           | 30                       | 10                             | 60                               | 10          |
|                           | 60                       | 418                            | 1197                              | 779         |                           | 60                       | 10                             | 60                               | 10          |
|                           | 100                      | 380                            | 1281                              | 901         |                           | 100                      | 493                            | 748                              | 255         |
|                           | 120                      | 364                            | 1320                              | 956         |                           | 120                      | 440                            | 825                              | 385         |
|                           | 150                      | 342                            | 1377                              | 1035        |                           | 150                      | 388                            | 912                              | 524         |
| 1.3                       | 10                       | 576                            | 816                               | 240         |                           | 10                       | 10                             | 60                               | 10          |
|                           | 30                       | 514                            | 902                               | 388         |                           | 30                       | 10                             | 60                               | 10          |
|                           | 60                       | 456                            | 995                               | 539         |                           | 60                       | 10                             | 60                               | 10          |
|                           | 100                      | 405                            | 1095                              | 692         |                           | 100                      | 493                            | 748                              | 255         |
|                           | 120                      | 381                            | 1139                              | 758         |                           | 120                      | 520                            | 642                              | 122         |
|                           | 150                      | 354                            | 1202                              | 848         |                           | 150                      | 416                            | 781                              | 365         |

**CHARACTERISTICS OF HYDROCARBON GAS HSZS**

**Calculation Method for Pure Methane HSZs.** Considering pure methane HSZs, their thickness and the top and bottom of the zone are mainly calculated by solving the simultaneous hydrate-phase equilibrium and geothermal gradient equation. Available hydrate-phase equilibrium equations of pure methane are based on the empirical equations proposed by Dickens et al., Brown et al., and Peltzer et al. and were obtained from experimental simulation data. The slope of the empirical equation proposed by Peltzer et al. quickly rises after the formation temperature exceeds 20 °C, revealing biogas genesis. The formation temperature is comprised of two separate parts: (1) the temperature of the frozen soil and (2) the...
temperature beneath the frozen soil. In this study, the geothermal gradient beneath the frozen soil was first calculated (eq 2). Then, the formation temperature of the frozen soil section followed only when the depth of the calculated pure methane HSZs was close to the bottom depth of the frozen soil.

In this study, considering the connectivity of the strata via microfractures to the surface, the formation pressure consists of both atmospheric pressure and the pressure equivalent to the column of fluid (eq 3). Constitutive equations for the model are as follows:36

\[
T = \frac{1}{T} = 3.83 \times 10^{-3} - 4.09 \times 10^{-4} \log_{10} P + 8.64 \times 10^{-5} (\log_{10} P)^2
\]  

\[
T = (h - D) \Delta T + 273
\]

\[
P = P_0 + \rho gh
\]

where \( T \) is formation temperature (K), \( P \) is formation pressure (MPa), \( h \) is depth (m), \( D \) is the thickness of frozen soil (m), \( \Delta T \) is the geothermal gradient (°C/100 m), \( P_0 \) is the atmospheric pressure (MPa), \( \rho \) is the density of the formation water (kg/m³), and \( g \) is the gravitational acceleration (N/kg).

The values of various variables in the equations were set as follows according to geological conditions of the Mohe Basin: \( D = 10–150 \) m (75–100 m for the main body) \( \Delta T = 1.0–1.6 \) °C/100 m, \( P_0 = 0.1 \) MPa, \( \rho = 1.0 \times 10^3 \) kg/m³, and \( g = 10 \) N/kg.

Considering 1.0 and 0.1 °C/100 m as the initial incremental values of the geothermal gradient, the thickness of a pure methane HSZ and its top and bottom depths were calculated based on the varying thicknesses of the frozen soil. Results are listed in Table 1 (thickness and the interval top and bottom depths), and the obtained critical parameters are shown in Figure 3.

### 2.2. Calculation Method of GHSZs.

An increase in the content of heavier hydrocarbon gas compounds in the guest molecules will expand temperature–pressure conditions for the formation of hydrates. As a result, natural gas hydrates can be formed under temperature–pressure conditions not sustainable for the formation of pure methane hydrates. Nonetheless, if natural gas HSZs (GHSZs) are precisely estimated, the amount of the potential reserve of hydrates in the Mohe Basin can be calculated. This would not be possible without a good knowledge of the various compounds that exist as guest molecules.

Based on what was said above, the minimum pressure at different temperatures for the stable existence of hydrates was first calculated using the CSMHYD program by knowing the composition of the gas produced in the Mohe Basin (Table 2).41 Next, the phase equilibrium curves of stable hydrates were obtained, then eq 4 was determined through empirical curve fitting. This enabled us to understand the occurrence of HSZs under different geothermal gradients and frozen soil thickness by solving eqs 3–5 simultaneously of the formation pressure, the temperature, and the hydrate-phase equilibrium curve.41

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**Figure 3.** Depth range of pure methane hydrate stability zones in the Mohe Basin. (a) Geothermal gradient ≤1.3 °C/100 m. (b) Geothermal gradient ≥1.6 °C/100 m.

**Table 2. Characteristics of Gas Hydrate Stability Zones under Different Formation Temperatures in the Mohe Basin with Certain Gas Compositions**

| geothermal gradient (°C/100 m) | frozen soil thickness (m) | burial depth of top boundary (m) | burial depth of bottom boundary (m) | thickness (m) | natural gas composition (%) |
|-----------------------------|-------------------------|-------------------------------|-----------------------------------|-------------|---------------------------|
| 1.6                         | 10                      | 75.5                          | 1419.0                            | 1343.5      | CH₄: 84                   |
|                             | 150                     | 60.6                          | 1589.3                            | 1528.7      | C₂H₆: 10                  |
| 2.3                         | 10                      | 81.5                          | 891.5                             | 810.0       | C₃H₈: 5                   |
|                             | 150                     | 60.8                          | 1071.2                            | 1010.4      | n-C₄H₁₀: 1                |

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**RESULTS**

**Results of Pure Methane HSZs.** The mean geothermal gradient in the Mohe Basin is 1.6 °C/100 m and the minimum geothermal gradient in the surrounding area is 1.0 °C/100 m, which was considered as the geothermal gradient in this study. Table 2 summarizes the top and bottom depths of pure methane HSZs and the thickness of the HSZs under a geothermal gradient of 1.0–1.6 °C/100 m and a frozen soil thickness of 10–150 m. According to Table 1, the top boundary of pure methane HSZs was at least 150 m below the bottom depth of the frozen soil. Therefore, it is unnecessary to also calculate the formation temperature in the frozen soil.

The temperature–pressure conditions for the stable existence of pure methane hydrates can be satisfied in most areas of the frozen soil under a geothermal gradient of ≤1.3 °C/100 m (Figure 3a). This means that such conditions cannot be met in areas of frozen soil when the formation temperature is ≥1.4 °C/100 m, since the frozen soil becomes very thin, and in most areas under the formation temperature of ≥1.6 °C/100 m (Figure 3b). Accordingly, when the maximum thickness of the frozen soil is 150 m under a normal pressure gradient, the conditions for the existence of pure methane HSZs cannot be met when the geothermal gradient reaches 1.7 °C/100 m.

It should be noted that the above calculations were done under normal formation pressure (0.8–1.3) conditions, with pure methane serving as the gas source. When abnormal high-pressure conditions prevail or wet gas is present as the main hydrocarbon source, the hydrate-phase equilibrium curve can get adjusted, resulting in wider temperature–pressure conditions appropriate for the formation of HSZs based on proposed theories of hydrate formation.36,42

**Results of GHSZs.** As stated above, pure methane hydrates can form in the case of a geothermal gradient of <1.6 °C/100 m, which also includes hydrates with wet gas as the source in this particular condition. Therefore, in this paper GHSZs are investigated in the case of a geothermal gradient of >1.6 °C/100 m and frozen soil thickness of 10 and 150 m. Results from the calculation are reported in Table 2. When geothermal gradient is 1.6 °C/100 m and the thickness of the frozen soil is 10 m, top and bottom depths of the HSZ are 75.5 m and 1419 m, respectively, and the corresponding HSZ thickness is 1343 m. Meanwhile, the top of the HSZ is 65.5 m below the bottom depth of the frozen soil (Figure 4a). Therefore, NGHs can form in the most areas of the Mohe Basin under the above formation temperature, frozen soil thickness, and gas source conditions. Furthermore, an increase in the frozen soil thickness will be more favorable for NGH formation. Additionally, GHSZ can also develop when the geothermal gradient is 2.3 °C/100 m and the frozen soil thickness is 10 m. Moreover, the top and bottom depths of the HSZ are 81.5 m and 1419 m, respectively, and the corresponding HSZ thickness will become 810 m (Figure 4b).

In Figure 4, the black arrow marks the bottom depth of the frozen soil, and the intersections of red dotted line and other
oblique lines indicate the top depth and the bottom depth of the hydrate stability zone.

**DISCUSSION**

The prediction of the occurrence of HSZs is mainly controlled by factors such as the mean annual ground surface temperature, the thickness of the frozen soil, the geothermal gradient, the formation pressure, the groundwater salinity, and the composition of guest molecules. These factors determine whether the formation temperature gradient curve can theoretically intersect with the hydrate-phase equilibrium curve to create an enclosed area between these two, which represents the formation conditions and depth interval occurrences of the HZS. Based on what has been presented so far, this paper discusses the factors that have a significant and direct impact on the presence and other characteristics of HSZs, such as the thickness of the frozen soil, the geothermal gradient, the formation pressure, and the composition of guest molecules.

**Influencing Factors of Temperature.** The formation temperature gradient curve of frozen soil consists of two separate sections with different slopes. The part with the steeper slope denotes a lower geothermal gradient, while the other part of the curve that is less steep represents the strata beneath the frozen soil. This means that the geothermal gradient is higher in the underlaying strata compared to that in the frozen soil. The inflection point where these two sections of the curve connect represents the bottom depth of the frozen soil, where the formation temperature is 0 °C. The thickness of the frozen soil determines the vertical extension of the formation temperature curve. Beneath the frozen soil, this curve moves deeper as the thickness of the frozen soil increases (Figure 4). As a result, the formation temperature curve is theoretically more likely to intersect with the hydrate-phase equilibrium curve, creating a larger envelope. This suggests that the top and bottom depths of the corresponding HSZ become shallower and deeper, respectively, creating a thicker HSZ (Figure 5). Generally, for every 10 m increase in the thickness of the frozen soil, the thickness of a pure methane HSZ would increase by 42.9–65.0 m.

There is a negative correlation between the slope of the formation temperature curve and the geothermal gradient. In other words, the slope of the formation temperature curve gradually decreases as the geothermal gradient increases. In this plot, the formation temperature curve rotates counterclockwise around the bottom depth of the frozen soil section. If the formation temperature curve originally intersects with the hydrate-phase equilibrium curve, the envelope will shrink after rotation, resulting in a sharp decrease in the thickness of the HSZ and a sharp increase in the bottom depth limit of the HSZ. Moreover, these two curves will not intersect once the geothermal gradient exceeds a certain value, meaning that the conditions for the existence of the HSZ cannot be satisfied (Figure 6). For instance, when the thickness of the frozen soil in the Mohe Basin is 100 m, the thickness of a pure methane HSZ will decrease from 1397 to 255 m, and the bottom depth limit of the HSZ will move upward from 1745 to 748 m as the geothermal gradient increases from 1.0 to 1.5 °C/100 m. That means that for every 0.1 °C/100 m increase in the average...
geothermal gradient, the thickness of the HSZ will decrease by 226.1 m and the bottom depth limit of the HSZ will increase in depth by 198.5 m. It is important to note that pure methane HSZs cannot be formed under a geothermal gradient \( \geq 1.6 \, ^\circ C/100 \, m \).

**Influencing Factors on the Hydrate Phase Equilibrium Curve.** The hydrate-phase equilibrium curve represents the temperature and pressure conditions that must be satisfied for the stable existence of hydrates. Otherwise, no hydrates can be formed. The influencing factors of the hydrate-phase equilibrium curve mainly include the formation pressure and the composition of guest molecules.\(^{47}\)

The formation pressure coefficient is the ratio of the formation pressure to the hydrostatic pressure, which has following formula:\(^{48}\)

\[
\alpha_p = \frac{p_f}{p_h} \quad (6)
\]

where \(\alpha_p\) is formation pressure coefficient, \(p_f\) is formation pressure (MPa), and \(p_h\) is the hydrostatic pressure (MPa).

According to the temperature–pressure equation of the hydrate-phase equilibrium (eq 4), the hydrate-phase equilibrium curve moves to the right in the plot as the formation pressure coefficient increases (Figure 7 and eq 6). Hence, the depth range where hydrates cannot normally be created under the formation pressure will accordingly become HSZs. Figure 7 shows that a pure methane HSZ cannot be seen when the thickness of the frozen soil is 100 m, the geothermal gradient is 2.0 \(^\circ C/100 \, m\), and the formation pressure coefficient is 1.2 (Figure 7a). In contrast, a pure methane HSZ can form at a depth interval of 350–600 m when the formation pressure coefficient increases to 1.3 (Figure 7b).

As explained by Milkov et al.\(^{49}\) based on the mechanisms that govern on the formation of hydrates in the Gulf of Mexico, the phase equilibrium curve of thermogenic wet gases moves right due to lower contents of methane and the higher amount of heavier gaseous hydrocarbon. As a result, in such zones where pure methane hydrates cannot form, the strata will become HSZs (Figure 8). Moreover, it was verified via the simulation of hydrate formation and decomposition that under the same temperature and pressure conditions, heavier gas molecules are more prone to turn into hydrates with a higher thermal stability than pure methane.\(^{3,4,50}\) This agrees with the simulation and calculation results in this study. It was found that pure methane HSZs cannot form under a geothermal gradient of 2.3 \(^\circ C/100 \, m\) and a permafrost thickness of 86 m. However, a HSZ with a thickness of 735 m can be found at a depth of 115–850 m when wet gas is present with a dryness coefficient of 0.88. When the source of guest molecules is wet gas with a dryness coefficient of 0.84, a HSZ with a thickness of 810.0 m can occur at a depth interval of 81.5–891.5 m even if the frozen soil is merely 10 m thick. Based on this finding, it
was concluded that the composition of the natural gas has significant effects on hydrate formation.

**Occurrence of GHSZs and Exploratory Well Suggestions.** Frozen soil mostly develops in lower altitudes in the Mohe Basin, such as marshes located among higher relief and montaneous areas, with an average thickness of 75–100 m and even up to 120 m individually. Based on the simulation results, pure methane hydrates are theoretically difficult to form in areas with a frozen soil thickness of 100 m and a geothermal gradient of \( \geq 1.6 \) °C/100 m. In other words, hydrates are difficult to form with a natural gas with a high dryness coefficient, such as the gas from the cracking of crude oil, kerogen, and biogas. Furthermore, HSZs can be found at a depth interval of 493–748 m only when the geothermal gradient is as low as 1.5 °C/100 m. Therefore, a pure methane HSZ with a thickness of at least 255 m can occur in areas in the Mohe Basin with a geothermal gradient of <1.5 °C/100 m. In such scenarios, the top and bottom depths of the HSZ are less than 493 m and more than 748 m, respectively.

An exploratory well, MK-2, was drilled near Beiji village in the north of the Mohe Basin, and an abnormally high amount of adsorbed gas was recovered from the cores at the depth interval of 800–1700 m via a desorption process.\(^{39,51}\) Such a phenomenon invalidates the findings of this study about the occurrence of pure methane HSZs. However, the chemical analysis of the natural gas composition from the core indicates the presence of heavier gas compounds with high dryness coefficients, which gradually decrease with depth to an average value as low as 0.88.\(^{39}\) Considering what was obtained by the simulation, a wet gas with a dryness coefficient of 0.88 can form a 735 m thick HSZ at a depth interval of 115–850 m under similar formation temperature and frozen soil conditions. Likewise, a gas with a lower dryness coefficient is favorable for hydrate formation, such as an associated gas and condensate.

Additionally, drilling has revealed that the Mohe Basin has a geothermal gradient of 1.6–2.3 °C/100 m and a frozen soil thickness of about 86 m and is normally pressured. Therefore, wet gas should be the main source for hydrate formation in the basin. The dryness coefficients of the gas obtained from the core analysis were mainly 0.89–0.90 at a depth range of 1400–1500 m and 0.84–0.88 at a depth range of 1600–1700 m,\(^{39}\) inferring that such wet gas sources exist in the basin.

Ultimately, drilling activities aimed at hydrate discovery have shown that source rocks in the Mohe Formation in the Mohe Basin have mostly advanced to the late oil-maturity stages.\(^ {39,52}\) Meanwhile, it has been proven that the dominant hydrocarbon products of such a thermal evolution of both source rocks and coal-bearing formations is gas condensate, which serves as the favorable source for hydrate formation. The gas can be supplied sufficiently in the peripheries of coal mines or primary oil and gas reservoirs, potentially leading to the creation of suitable intervals of potential hydrate-bearing zones in the Mohe Basin. Based on the results from the theoretical calculation obtained here and the geological conditions of the basin, the final depth of hydrates in the Mohe Basin can be approximately 800 m considering the following facts. First, the most favorable depth range of HSZs was calculated to be 493–748 m, and the temperature–pressure conditions for hydrate discovery can be met at a depth less than 800 m. Second, the bottom depth limit of hydrate resources is mostly less than 800 m in the permafrost areas with lower gas dryness coefficient, a geothermal gradient less than 1.5 °C/100 m, a thick frozen soil layer, and of course a gas supply such as the Alaska North Slope in the United States and Messoyakha in Siberia. It should be noted that the Mohe Basin is located in lower latitudes than these areas, causing the burial depth of the hydrate resources to be less than 800 m. Third, the thickness of the frozen soil, the geothermal gradient, and the formation pressure can be accurately obtained via drilling data. Finally, integrating theoretical models applied in this study with field data can assist us in locating favorable and enriched areas of hydrates more accurately for future discoveries.

**CONCLUSIONS**

The HSZ occurrence in the Mohe Basin is mainly controlled by factors such as the thickness of the frozen soil, the formation pressure, the geothermal gradient, and the composition of the gas as the guest molecules, with the last two having the most prominent effects. Based on the results, a pure methane HSZ with a thickness of about 255 m at minimum can form in areas with a geothermal gradient less than 1.5 °C/100 m. Meanwhile, the top and bottom depth limits of the HSZ are less than 493 m and more than 748 m, respectively. In contrast, pure methane hydrates are difficult to form where there is a geothermal gradient greater than 1.6 °C/100 m. However, when the wet gas with a dryness coefficient of 0.84 is the source of the guest molecules, a HSZ with a thickness of 810.0 m can be expected even under a geothermal gradient up to 2.3 °C/100 m and a frozen soil thickness of only 10 m.

Ultimately, it was concluded that the Mohe Basin is one of the major terrestrial-hydrate-prolific areas in China, and wet gas with a high content of heavier hydrocarbon gas molecules is the source of hydrate formation in the basin. We concluded that areas adjacent to coal mines or primary oil or gas reservoirs can provide the gas supply as guest molecules and become the potential hydrate-bearing zones because of suitable \( P-T \) conditions of the formation.

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Notes
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