A preliminary study of the gas hydrate stability zone in a gas hydrate potential region of China

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Abstract
Due to its significance for gas hydrate accumulation, the gas hydrate stability zone (GHSZ) is an essential condition for successful gas hydrate exploration and is usually controlled by three main factors: gas components, geothermal gradient, and permafrost thickness. Based on the core and conventional log data of gas hydrate potential region, the CSMHYD program was adopted to simulate the influences of above three factors on the thickness of the GHSZ. When the gas components of the gas hydrate were CH4, C2H6, and C3H8, with the CH4 percentage ranging from 50% to 100%, the average GHSZ thickness can reach 1000 m according to the forward simulation results. When the gas hydrate was composed of CH4 and one of C2H6, C3H8, H2S, and CO2, the influence order of the above four gases on the thickness of GHSZ is as follows: H2S > C2H6 > C3H8 > CO2. Under the gas components of 90% CH4, 5% C2H6, and 5% C3H8, the thickness of GHSZ decreased rapidly as the geothermal gradient increased following an exponential relation with a correlation of 99.92% and increased slowly as permafrost thickness increased following a linear relation with a correlation of 99.9%. In addition, the thickness of a gas hydrate favorable reservoir was determined by comprehensive log methods as 500 m. We conclude that a reservoir within 500 m below the permafrost layer is favorable for gas hydrate reservoir formation.

KEYWORDS
gas hydrate, gas hydrate stability zone, influence factor, numerical simulation, well log data

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Gas hydrate is a solid crystal with a cage-like structure consisting of water molecules and natural gas (mainly CH₄), which mainly exists at the bottom of the sea and within and beneath polar permafrost. It occurs in permafrost regions at depths of 200-2000 m on the continents, in deep water basins of 300-3000 m deep, and beneath the slope breaks of continental shelves in the ocean. As a new cleaner alternative energy source of huge reserve, gas hydrate has attracted more and more attention, and more than 100 regions have directly or indirectly found occurrences of gas hydrate zones. In China, gas hydrate samples were acquired successfully in the Shenhu area of the South China Sea in May 2007 and were obtained by drilling for the first time in the Qilian Mountain permafrost region of Qinghai Province in November 2008. In recent years, some systematic investigations, including geological methods, geophysical methods, and geochemical methods, were carried out in gas hydrate potential regions of China, and the results showed that these permafrost regions had a good prospect for the formation and accumulation of gas hydrates. These researches have greatly promoted the process of gas hydrate prospecting in permafrost regions of China.

In the formation of gas hydrate, three conditions of low temperature, high pressure, and ample gas source must be satisfied at the same time. Among these conditions, the gas source must be sufficient, and the temperature and pressure are necessary conditions and root causes, which represents the possible scope for the existence of gas hydrate. Therefore, the influences of the 3 parameters on gas hydrate formation have become one of the topics of focus in the study of gas hydrate. The gas hydrate potential region is usually located in the high latitude regions of China, which has good gas hydrate formation conditions, and which are favorable for the development of a gas hydrate reservoir. However, the related work about temperature and pressure conditions for gas hydrate formation and accumulation in this area is scarce, and the understanding on the distribution range of GHSZ is still superficial. Therefore, the systematic research of GHSZ and the related analysis of influence factors are significant for revealing the potential distribution of gas hydrate and identification of favorable gas hydrate reservoirs in the permafrost regions.

From 2011, China Geological Survey conducted a series of scientific drilling boreholes in the permafrost regions of China, and comprehensive investigations such as geological, geophysical, drilling, and other surveys were also carried out. Geophysical well logging can measure physical parameters under the in situ formation conditions of pressure and temperature, which is an effective method for identifying and evaluating gas hydrates. The researchers participated in the comprehensive geophysical logging work of above scientific drilling boreholes and acquired integrated log data, such as temperature, density, acoustic velocity, and acoustic imaging logs, which can provide valuable basic data for analysis and evaluation of GHSZ in this research area. The integrated log data were acquired using a digital well logging system developed by Mount Sopris Instrument Company. In this paper, we first adopt the CSMHYD program to simulate the thickness of the GHSZ and then analyze the influences of gas components, geothermal gradient, and permafrost thickness on the GHSZ thickness. This work can provide the basic technical support for gas hydrate exploration in the research area and lay a foundation for predicting and assessing the amount of a gas hydrate resource.

The formation of gas hydrate is a three-phase balance process between gas hydrate, water, and gas. The GHSZ is delineated by the temperature-pressure phase equilibrium surface and the geothermal gradient curve as shown in Figure 1, where the temperature and pressure in the GHSZ are in the thermodynamic stability range for gas hydrate formation. Thus, in the permafrost, the gas hydrate thermodynamic stability zone, namely GHSZ, is limited by the surface temperature, the geothermal gradient in the permafrost, the geothermal gradient beneath the permafrost, and the temperature-pressure phase equilibrium boundary of gas hydrate formation and stability. The upper intersection of the geothermal gradient with the permafrost and temperature-pressure phase equilibrium boundary is the top boundary of the GHSZ, and the lower intersection of geothermal gradient under the permafrost and temperature-pressure phase equilibrium boundary is the bottom boundary of the GHSZ. Obviously, the stability zone between the two intersections is the zone of gas hydrate formation in theory. Notably, temperature and pressure are the major determining factors for phase equilibrium of the gas hydrate.
system and are essential conditions for gas hydrate formation. In this paper, through numerical simulation of CSMHYD program, we analyzed the measured log data of typical scientific drilling borehole in the determination of potential GHSZ.

Sloan studied the temperature-pressure phase equilibrium conditions of gas hydrates with different gas components and developed phase equilibrium numerical simulation program (CSMHYD).1 The program could not only calculate the temperature at given pressures and the pressure at given temperatures of pure water, but could also simulate the temperature and pressure of seawater and pore water under different salinities. Many scholars carried out theoretical analyses and experimental research to study the phase equilibrium conditions of gas hydrate and further established the relations between critical temperature and pressure in the phase transformation of gas hydrates with different gas components.27-34 In the temperature-pressure diagram, the relationship can be represented by the phase equilibrium curve, and the pressure parameters can be converted into depth parameters when only considering the hydrostatic pressure of overlying strata. Therefore, the depth-temperature diagram can be used to replace the pressure-temperature diagram. Meanwhile, the relations between pressure of the permafrost and the sediment under the permafrost and depth can be, respectively, calculated according to the lithostatic pressure ($P_f$) and static water pressure ($P_s$).35 The mathematic formulas can be expressed as follows:

\begin{align}
  P_f &= P_0 + \rho_f g h_f 10^{-6} \\
  P_s &= P_f + \rho_s g h_s 10^{-6}
\end{align}

where $P_0$ is the atmospheric pressure at the Earth’s surface with the value of 0.1 MPa, $g$ is the gravitational acceleration constant with the value of 9.81 m/s², $\rho_f$ (kg/m³) is the density of the permafrost, $\rho_s$ (kg/m³) is the pore fluid density under the permafrost, $h_f$ (m) is the depth within the permafrost, and $h_s$ (m) is the depth below the bottom of the permafrost.

The geothermal gradient inside and beneath the permafrost can be determined by the relationship between temperature and depth as follows35:

\begin{align}
  t_f &= t_0 + G_f h_f \\
  t_s &= t_{f0} + G_s h_s
\end{align}

where $t_f$ (°C) is the temperature at the depth of $h_f$ in the permafrost, $t_0$ (°C) is the temperature at the Earth’s surface, $G_f$ (°C/m) is the geothermal gradient in the permafrost, $t_s$ (°C) is the temperature at the depth of $h_s$ beneath the permafrost, $t_{f0}$ (°C) is the temperature of the bottom boundary of the permafrost, and $G_s$ (°C/m) is the geothermal gradient beneath the permafrost.

### RESULTS AND ANALYSES

#### 3.1 Numerical simulation of the GHSZ thickness

The temperature and pressure conditions for gas hydrate formation are the most restrictive when the component is pure CH₄, whereas the phase equilibrium curve can shift to the

| Gas components | Temperature and pressure conditions |
|----------------|-----------------------------------|
| CH₄ = 100%     | T (°C)   | -10 | -5 | 0 | 5 | 10 | 15 | 20 | 25 | 30 |
|                | P (MPa)  | 1.93 | 2.24 | 2.64 | 4.24 | 6.95 | 11.85 | 21.29 | 38.54 | 65.81 |
|                | D (m)    | 114.54 | 146.14 | 186.92 | 350.02 | 626.27 | 1125.76 | 2088.04 | 3846.21 | 7004.51 |
| CH₄ = 90%     | P (MPa)  | 0.45 | 0.55 | 0.67 | 1.22 | 2.20 | 4.05 | 8.24 | 21.25 | 44.58 |
| C₂H₆ = 5% | D (m)    | 13.68 | 17.62 | 22.41 | 43.93 | 142.12 | 330.82 | 757.33 | 2084.25 | 7004.51 |
| C₃H₈ = 5%     |          |          |          |          |          |          |          |          |          |
| CH₄ = 80%     | P (MPa)  | 0.34 | 0.41 | 0.50 | 0.94 | 1.73 | 3.20 | 6.39 | 17.07 | 38.35 |
| C₂H₆ = 10%    | D (m)    | 9.31 | 12.23 | 15.77 | 33.03 | 94.26 | 244.13 | 569.51 | 1657.97 | 3827.14 |
| C₃H₈ = 10%    |          |          |          |          |          |          |          |          |          |
| CH₄ = 70%     | P (MPa)  | 0.29 | 0.35 | 0.43 | 0.83 | 1.55 | 2.91 | 5.89 | 16.40 | 37.00 |
| C₂H₆ = 15%    | D (m)    | 7.36 | 9.84 | 12.82 | 28.43 | 75.58 | 214.12 | 518.27 | 1590.04 | 3688.82 |
| C₃H₈ = 15%    |          |          |          |          |          |          |          |          |          |
| CH₄ = 60%     | P (MPa)  | 0.26 | 0.32 | 0.38 | 0.76 | 1.47 | 2.82 | 5.92 | 17.03 | 37.94 |
| C₂H₆ = 20%    | D (m)    | 6.24 | 8.46 | 11.13 | 26.05 | 67.51 | 204.81 | 521.68 | 1653.80 | 3785.51 |
| C₃H₈ = 20%    |          |          |          |          |          |          |          |          |          |
| CH₄ = 50%     | P (MPa)  | 0.24 | 0.29 | 0.36 | 0.73 | 1.45 | 2.86 | 6.47 | 18.70 | 40.85 |
| C₂H₆ = 25%    | D (m)    | 5.55 | 7.61 | 10.08 | 24.87 | 65.65 | 208.92 | 576.85 | 1823.65 | 4082.32 |
| C₃H₈ = 25%    |          |          |          |          |          |          |          |          |          |

Note: T represents temperature, P represents pressure, and D represents depth.
right to enlarge the GHSZ scope when the gas hydrate contains heavier hydrocarbons such as C\textsubscript{2}H\textsubscript{6} and C\textsubscript{3}H\textsubscript{8}, which facilitates the formation of gas hydrate over a wider range of temperature and pressure. According to the reported percentage relations of gas hydrates with different gas components, the gas components of gas hydrate in this study are selected as CH\textsubscript{4}, C\textsubscript{2}H\textsubscript{6}, and C\textsubscript{3}H\textsubscript{8}, and the variation range of CH\textsubscript{4} is 50%-100%\cite{6,36-39}. Thus, we can obtain the temperature-pressure conditions for gas hydrate formation through the numerical simulation of the CSMHYD program (Table 1), and the phase equilibrium curves of gas hydrate can be drawn based on the data.

Figure 2 shows the temperature log curves measured from the temperature log, which can be used as the basis for determining the GHSZ. Due to the temperature effect of the Earth’s surface, the measured temperature data have a large perturbation at depths of 0-100 m, which leads to the fluctuation of the estimated geothermal gradient from Equation (4). The depth at which temperature curve is 0°C can be determined as the bottom boundary of permafrost. Here, the depth of the bottom boundary of the permafrost is determined as 45 m, and the average value of geothermal gradient under the permafrost is estimated as 2.23°C/100 m according to Equation (4).

Using the temperature and pressure data of different gas components in Table 1 and the measured temperature data from the temperature log, the distribution map of GHSZ can be drawn using the temperature-pressure conditions for gas hydrate formation from the numerical simulation of the CSMHYD program. As Figure 3 shows, when the gas hydrate is composed of pure CH\textsubscript{4}, there is no intersection between the geothermal gradient curve and its corresponding phase equilibrium curve, which means the GHSZ cannot be formed; however, when the gas hydrate contains heavy hydrocarbons such as C\textsubscript{2}H\textsubscript{6} and C\textsubscript{3}H\textsubscript{8}, the phase equilibrium curve moves quickly to the right and intersects with the geothermal gradient curve, thus forming the GHSZ.

Due to the lack of temperature monitoring devices for the Earth surface, it is difficult to determine the Earth surface temperature, so that the geothermal gradient in the permafrost cannot be calculated. In this work, we approximately take the intersection of the vertical line of permafrost bottom boundary and the temperature-pressure phase equilibrium curve as the top boundary of GHSZ, and the corresponding buried depths that intersect with the top boundary are, respectively, 22, 16, 13, 11, and 10 m when the CH\textsubscript{4} percentages of gas hydrate are 90%, 80%, 70%, 60%, and 50%, respectively, with the average burial depth of 14.4 m. The intersection of geothermal gradient curve under the permafrost and temperature-pressure phase equilibrium curve can be considered as the bottom boundary of GHSZ, and the corresponding burial depths that intersect with the bottom boundary are,
respectively, 1000, 1070, 1080, 1090, and 1045 m when the CH₄ percentages of gas hydrate are 90%, 80%, 70%, 60%, and 50%, respectively, with the average buried depth of 1042.6 m. Based on these results, the corresponding thickness of GHSZ with different gas components are, respectively, 978, 1054, 1067, 1079, and 1035 m, with the average value of 1042.6 m. Therefore, we can deduce according to the above analysis of temperature-pressure conditions for gas hydrate forming that the GHSZ thickness is quite large and that there are large prospects for gas hydrate in the research area.

### 3.2 Influence of gas components on the thickness of GHSZ

Gas is the material basis for gas hydrate accumulation. At present, there are two kinds of gas sources that can form gas hydrate in the natural environment: biogenetic gas and pyrolysis gas. Biogenic gas is basically composed of CH₄, while pyrolysis gas may contain small amounts of other gases such as C₂H₆, C₃H₈, H₂S, and CO₂ in addition to CH₄. Previous studies indicate that different gas components influence the temperature-pressure phase equilibrium curve of gas hydrate and further affect the thickness of GHSZ.⁴¹,⁴²

Using the temperature log data from the borehole, the influence of different gas components on the GHSZ thickness has been simulated using the CSMHYD program. We assume that the gas components of gas hydrate are composed of CH₄ and one of C₂H₆, C₃H₈, H₂S, and CO₂ and that the range of the four gases varies from 5% to 20%. We assume the geothermal gradient beneath the permafrost to be 22.3°C/km and the permafrost thickness as 45 m. Thus, the GHSZ thickness formed by different gas components can be calculated, as shown in Figure 4 and Table 2. It can be seen that the different gas components influence the GHSZ thickness and that the GHSZ cannot be formed due to the presence or absence of some gases, for example when the CO₂ percentage is less than 20%. In general, the GHSZ thickness increases with the increase of different gas components.

From Table 2, the influence of the above four gases on the GHSZ thickness keeps to the following order: H₂S > C₂H₆ > C₃H₈ > CO₂. H₂S has the most significant influence on the thickness of GHSZ. As the H₂S percentage
increases from 0% to 20%, the GHSZ thickness increases by 360 m. In contrast, CO₂ has the weakest influence on the thickness of GHSZ, and the GHSZ begins to appear until the CO₂ percentage increases to 20% so that temperature-pressure phase equilibrium curve of gas hydrate can intersects geothermal gradient curve.

3.3 Influence of geothermal gradient on the thickness of GHSZ

An appropriate geothermal gradient is vital for gas hydrate occurrence and GHSZ thickness. In view of this, we use numerical simulation to investigate the influence of different geothermal gradients on the GHSZ thickness. According to previous research, the geothermal gradient varies in the range of 10 to 45.4°C/km in the research region, which is similar to other areas where gas hydrate has been found. If we assume the gas components of the gas hydrate are composed of 90% CH₄, 5% C₂H₆, and 5% C₃H₈. We select range for the geothermal gradient as 10 ~ 50°C/km and set the permafrost thickness to be 45 m. Then, the thickness of GHSZ formed by different geothermal gradients can be calculated. As Figure 5 shows, when the geothermal gradient is 10, 20, 30, 40, and 50°C/km, the corresponding thickness of GHSZ is 2689, 1134, 689, 469, and 339 m, respectively, and the decreasing rate is up to 87.39%, which confirms the great effect of geothermal gradient on the thickness of GHSZ. As the geothermal gradient increases, the GHSZ thickness decreases rapidly following an exponential relationship with the correlation up to 99.92%.

3.4 Influence of permafrost thickness on the thickness of GHSZ

Permafrost thickness is closely related to the formation and preservation of gas hydrate. According to previous research, the permafrost thickness in the research area presents an increasing trend toward the northwest with the thickness ranging from 0 to 100 m, which is very close to other areas where gas hydrates have been found. We assume the gas components of the gas hydrate are 90% CH₄, 5% C₂H₆, and 5% C₃H₈ and select the permafrost thickness range to be from 0 to 100 m and the geothermal gradient as 2.23°C/100 m. Then, the thickness of the GHSZ formed in association with the different permafrost thicknesses can be numerically simulated. As Figure 6 shows, when the permafrost thickness increases from 0 to 100 m, the

| TABLE 2 | GHSZ thickness of different gas components |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Gas components | Gas percentage | Gas percentage | Gas percentage | Gas percentage |
| C₂H₆           | 5%             | 10%            | 15%            | 20%            |
|                | 545            | 730            | 780            | 835            |
| C₃H₈           | 10%            | 1120           | 1180           | 1200           |
| H₂S            | 900            | 1070           | 1200           | 1260           |
| CO₂            | 0              | 0              | 0              | 445            |

FIGURE 5  The relationship between the geothermal gradient and the GHSZ thickness. In the left figure, red curve represents the temperature-pressure phase equilibrium curve when gas components of the gas hydrate are 90% CH₄, 5% C₂H₆, and 5% C₃H₈; blue, pink, turquoise, violet, and yellow curves represent the situations when the geothermal gradient beneath the permafrost is 10, 20, 30, 40, and 50°C/km, respectively. In the right figure, pink curve represents the relationship between the geothermal gradient beneath the permafrost and the thickness of the GHSZ; whereas blue curve represents the exponential fitting curve of those two parameters.
corresponding GHSZ thickness increases from 975 to 1015 m with an increasing rate of 4.1%, which indicates that permafrost thickness has little effect on the thickness of GHSZ. As the permafrost thickness increases, the GHSZ thickness increases slowly following a linear trend with the correlation up to 99.9%.

Through the above analysis, it can be concluded that the geothermal gradient has the greatest effect on the thickness of GHSZ, followed by the relative gas components, and lastly the permafrost thickness. A lower geothermal gradient is conducive to gas hydrate occurrence, so that an appropriate geothermal gradient is crucial for gas hydrate formation in the research area. As for gas components, the gas hydrate containing heavy hydrocarbons (C2H6, C3H8) can prompt the enlargement of the gas hydrate concentration region. Lastly, the permafrost thickness appears to have little effect on the thickness of GHSZ, and a certain permafrost thickness can satisfy the condition of a cap layer for gas hydrate storage.

4 | DISCUSSION

Since the density of gas hydrate is close to the density of formation water, the porosity calculated from the density log can be approximately indicative of the total porosity of the formation, including the porosity of fracture filling gas hydrate and the porosity of saturated water. The more developed the formation porosity, the more likely it is to have gas hydrate in the formation. Therefore, the calculated porosity log can be used as an effective method for favorable reservoir identification. The ultrasonic imaging log is useful for effectively identifying formation fractures and fractured zones, evaluating the types and occurrences of fractures, and analyzing sedimentary characteristics of the formations. The more developed the formation fracture, the more likely it is to have gas hydrate in the formation. Therefore, the ultrasonic imaging log can also be used as an effective method for favorable reservoir identification. These two types of log methods can be used to check the accuracy of the other log and for the predicted favorable reservoir.

4.1 | Identifying the favorable reservoir of gas hydrate by porosity log methods

One of the main goals of gas hydrate reservoir evaluation is delineating a favorable reservoir by determining the formation porosity. The density log, acoustic velocity log, and resistivity log data are generally used to calculate the sediment porosity of a gas hydrate zone. When it comes to the determination of sediment porosity from the resistivity log, the Archie formula should be used to calculate porosity, and the Archie constants and formation water resistivity need to be known for the Archie formula. The above two parameters

![Figure 6](image)

**Figure 6** The relationship between the permafrost thickness and the GHSZ thickness. In the left figure, dark blue, red, yellow, turquoise, violet, deep red, cyan, blue, sky blue, light blue, and green curves, respectively, represent the temperature-pressure phase equilibrium curves when the permafrost thickness is 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 m; red curve represents the geothermal gradient curve beneath the permafrost of temperature log of the borehole. In the right figure, red curve represents the relationship between the permafrost thickness and the GHSZ thickness; blue curve represents the linear fitting curve of those two parameters.
are generally determined by some empirical equations based on experimental data. Due to a lack of experimental data from the core of the borehole, the two parameters cannot be determined. Therefore, we use the density log and acoustic log in this study to evaluate the apparent sediment porosity.

The estimation of sediment porosity from the density log data can be expressed as:

$$\phi_d = \frac{\rho_{ma} - \rho_{f}}{\rho_{ma} - \rho_{b}}$$

(5)

where $\phi_d$ is the sediment porosity, $\rho_{ma}$ is the matrix density, $\rho_{b}$ is the volume density of rock from the density log, and $\rho_{f}$ is the fluid density. In the process of borehole estimation, $\rho_{ma}$ uses the average matrix density of sandstone, which is 2.67 g/cm$^3$, and $\rho_{f}$ uses the approximate formation water density, which is 1.00 g/cm$^3$.

The estimation of sediment porosity from the acoustic velocity log data can be expressed as:

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_{f} - \Delta t_{ma}}$$

(6)

where $\phi_s$ is the sediment porosity, $\Delta t$ is the interval transit time from the acoustic velocity log, $\Delta t_{ma}$ is the interval transit time of the matrix, and $\Delta t_{f}$ is the interval transit time of the pore fluid. In the process of the borehole estimation, $\Delta t_{ma}$ uses the interval transit time of sandstone, which is 182 $\mu$s/m, and $\Delta t_{f}$ is the interval transit time of formation water, which is 620 $\mu$s/m.

Equations (5) and (6) are used to calculate the apparent sediment porosity. Because the greatest depth of GHSZ is close to 1100 m, the sediment porosity in depth of 0-1100 m is selected for analysis (Figure 7). Because the logging detector system is measured in slim-hole condition, the measurement result may be influenced. The error of estimation of sediment porosity of the borehole by the porosity log methods is large, so the sediment porosity calculated by the porosity log methods is only used for qualitative evaluation. Based on the core data, the slate, mylonite, metamorphic sandstone, metamorphic siltstone, and other metamorphic rocks are exposed. The corresponding sediment density will be high, and the corresponding interval transit time will be small. So Equations (5) and (6) that are based on the sandstone formation parameters which are used to estimate sediment porosity will make the density porosity small and acoustic porosity large in some layers. As the favorable reservoir of gas hydrate is in the sandstone and mudstone layers with developed fracture, the porosity of metamorphic rock in the borehole can be largely ignored. The average value of density porosity at depths of 0-500 m is 9.44%. The calculated density porosity in some intervals has a large fluctuation because of the influence of the borehole condition. The average value of acoustic porosity is 8.65% which reflects the large sediment porosity in this interval. The depth of 0-500 m is the favorable depth range for gas hydrate reservoir occurrence. The density porosity at depths of 500-1100 m is close to 0 which illustrates that most of the formation lithology is dense and more metamorphic rocks are exposed. The depth of 500-1100 m is not the favorable depth range for gas hydrate reservoir occurrence. To sum up, the depth interval of 0-500 m of the borehole is the favorable zone for gas hydrate occurrence as determined from the porosity log methods.

4.2 Identifying the favorable reservoir of gas hydrate by ultrasonic imaging logging method

In the gas hydrate regions of the world, there are two different ways for gas hydrate occurrence in sedimentary strata. One occurs in the fractures of the rock, whereas the other occurs in the pores of the rock. This suggests that degree of the formation fracture development is vital for the formation and enrichment of gas hydrate. Ultrasonic imaging logging can reflect in situ geological characteristics of the borehole
**FIGURE 8** Typical fracture zone of the borehole

| Caliper | Depth (1 m:50 m) | Resistivity (Ω.m) | Density (g/cm³) | Acoustic imaging logging image |
|---------|------------------|-------------------|-----------------|-------------------------------|
| 5 in    | 8                | 1                 | 10000           | 0                             |
| Gamma ray |                 |                   |                 | API 100                       |
| 0       | 100             | 1000 m/s          | 6000            |                               |

**FIGURE 9** Fracture parameters changing with depth (Fracture frequency statistics interval is 10 m in first figure.)
wall and effectively identify formation fractures and fracture zones. Therefore, ultrasonic imaging logging can be used to evaluate the type and occurrence of formation fractures, analyze strata sedimentary characteristics, identify favorable gas hydrate reservoir, etc.

The processing of ultrasonic imaging log data includes pretreatment, image generation, interactive processing, and interpretation. For this borehole, WellCAD software by Advanced Logic Technology Company was used to process log data. The Image Log processing module of WellCAD software conducts a series of pretreatments of the ultrasonic imaging log data, including filtering, interpolation, normalization, statistical information, directional information, and mirrored images of the data. This module can also adjust the eccentricity of the instrument and generate caliper images. The Structure Log processing module of WellCAD software can interactively gather geological structure occurrences (such as bedding, bed interface, and fracture), estimate fracture apertures and fractured zone thickness, and segmented counts of the occurrence data.

The typical fracture zone can be identified by well logging at the depth of 175 m of the borehole (Figure 8). The image displays dark stripe on the acoustic imaging logging. The values of caliper and gamma ray increase, but the values of resistivity, density, and acoustic velocity decrease on the conventional logging. The multiple layers of the borehole are fracture zones that can reflect the developed fractures of these layers and are favorable reservoirs for gas hydrate formation.

Based on the fracture distribution in the images from the acoustic imaging logging method, more than 1600 fractures have been located at depths of 0 to 1700 m in the borehole. The fracture parameters were calculated, and fracture distribution characteristics were analyzed. Fracture frequency statistical results are shown in Figure 9. The absolute frequency of the borehole is 0.96 (the interval is 1 m). The high angle fracture is the main fracture type in the borehole, and dip angles of the fractures are mainly distributed in the range of 45°-75°. Sediment fractures are especially developed at depths of 0-500 m in the borehole, and the absolute frequency in this section reaches 2.09 (the interval is 1 m). The depth interval of 0-500 m is a favorable zone for gas hydrate occurrence. The result is consistent with the favorable reservoir of gas hydrate that was estimated by porosity logging methods.

5 | CONCLUSIONS

1. When the gas components of the gas hydrate are CH4, C2H6, and C3H8 in association with the CH4 percentage ranging from 50% to 100%, the average GHSZ thickness from the forward simulation results can be as high as 1000 m, which provides an extensive reservoir space for gas hydrate occurrence in the research area.

2. The addition of different gas components has a significant influence on the thickness of GHSZ. As gas components of the gas hydrate are CH4 and one of C2H6, C3H8, H2S, and CO2, the influence of the above four gases on the GHSZ thickness follows the order of influence: H2S > C2H6 > C3H8 > CO2.

3. When the gas components of the gas hydrate are 90% CH4, 5% C2H6, and 5% C3H8, the thickness of GHSZ decreases rapidly as the geothermal gradient increases, which follows an exponential relationship with the correlation up to 99.92%. With the same gas components, the thickness of GHSZ increases slowly with the increase of permafrost thickness, which follows a linear relationship with a correlation up to 99.9%.

4. Using the porosity logging methods, the thickness of a favorable gas hydrate reservoir can be 500 m, which is consistent with the results from the acoustic imaging logging method. It can be concluded that the reservoir within 500 m below the permafrost is favorable for gas hydrate formation and retention.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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