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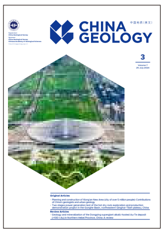

Geological reservoir and resource potential (10^{13} m^3) of gas hydrates in the South China Sea

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ABSTRACT

A detailed understanding of the distribution and potential of natural gas hydrate (NGHs) resources is crucial to fostering the industrialization of those resources in the South China Sea, where NGHs are abundant. In this study, this study analyzed the applicability of resource evaluation methods, including the volumetric, genesis, and analogy methods, and estimated NGHs resource potential in the South China Sea by using scientific resource evaluation methods based on the factors controlling the geological accumulation and the reservoir characteristics of NGHs. Furthermore, this study compared the evaluation results of NGHs resource evaluations in representative worldwide sea areas via rational analysis. The results of this study are as follows: (1) The gas hydrate accumulation in the South China Sea is characterized by multiple sources of gas supply, multi-channel migration, and extensive accumulation, which are significantly different from those of oil and gas and other unconventional resources. (2) The evaluation of gas hydrate resources in the South China Sea is a highly targeted, stratified, and multidisciplinary evaluation of geological resources under the framework of a multi-type gas hydrate resource evaluation system and focuses on the comprehensive utilization of multi-source heterogeneous data. (3) Global NGHs resources is $n\times10^{15}$ m^3, while the NGHs resources in the South China Sea are estimated to be 10^{13} m^3, which is comparable to the abundance of typical marine NGHs deposits in other parts of the world. In the South China Sea, the NGHs resources have a broad prospect and provide a substantial resource base for production tests and industrialization of NGHs.

1. Introduction

Natural gas hydrate (NGHs) is a collective term for a group of NGHs and associated gases that are generated and exist in natural strata under natural conditions and can be exploited by humans through various means and methods. These deposits possess distinctive characteristics, including a shallow burial depth, extensive distribution, large scale, and potential for clean and efficient utilization. NGHs deposits with resource properties have been identified as being prevalent in permafrost regions of the Arctic and deep-water regions in the majority of continental margins around the globe (Fig. 1). The thickness of gas hydrate deposits varies considerably, from a few centimeters to hundreds of meters, and their distribution area extends from thousands of square meters to hundreds of thousands of square kilometers. The gas resources in a single sea area can reach several trillion to a hundred trillion cubic meters. Although the geological background of gas hydrate accumulation is complex, reservoir identification is challenging, and there are numerous uncertain factors in resource potential recognition, it has been well accepted that the natural gas resources host in gas hydrate resources far exceed the known natural gas reserves (Boswell R and Collett TS, 2011; Collett TS, 2002). A third test on the exploitation of gas hydrates in the South China Sea is

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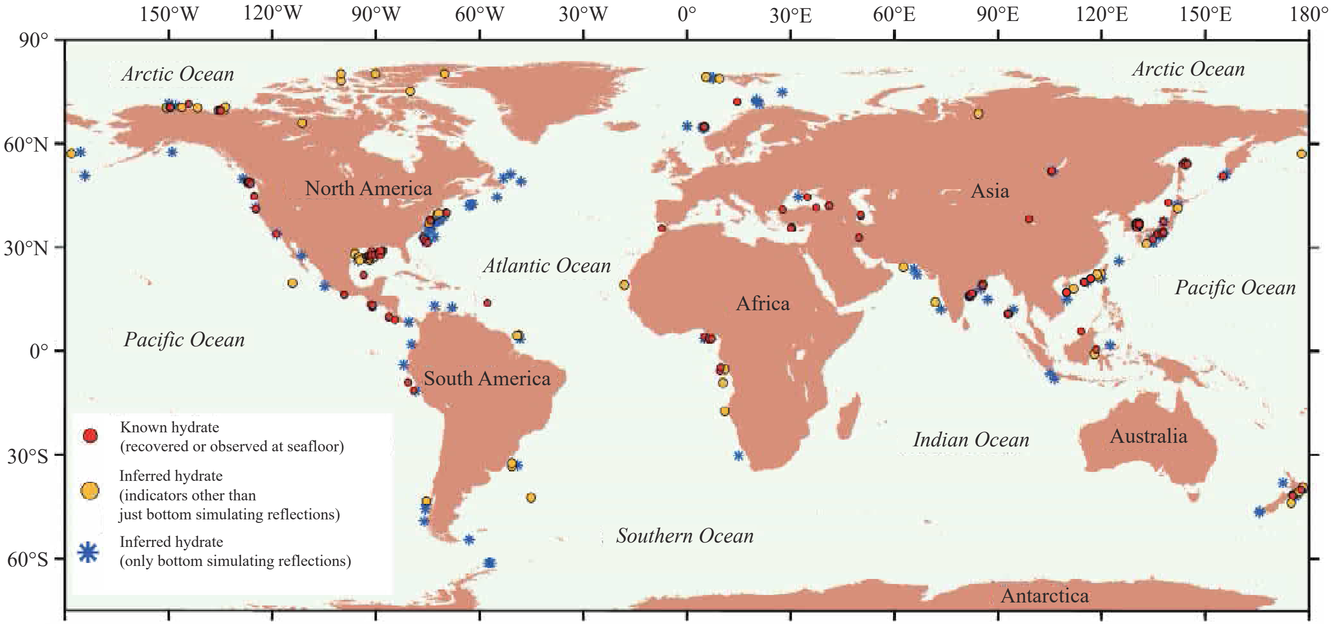

Fig. 1. Global overview of the distribution of natural gas hydrates (modified from Waite WF et al., 2020).

imminent. Due to the development and auccess of technology that has been developed, the potential of the gas hydrate resources in the South China Sea has become a significant interest in all sectors of society. In this study, we developed a reasonable and feasible approach for the evaluation of gas hydrate resources based on a geological assessment of the factors that control the accumulation of gas hydrates and the characteristics of the mineral reservoirs. This study aimed to estimate the amount of geological resources of gas hydrate in the South China Sea and to engage in a rational analysis and discussion of the findings.

2. Geological factors controlling gas hydrate accumulation

Clarifying the geological factors controlling gas hydrate accumulation is an important step in improving the accuracy of predicting gas hydrate resources. Compared with conventional oil and gas resources, gas hydrate accumulation has a diversity of sources and migration pathways, a broader reservoir area, and a greater resource potential. From the perspective of the formation, migration, and accumulation of marine NGHs, the NGHs reservoirs in the South China Sea are characterized by multi-source supply, multi-channel transport, and extensive accumulation.

2.1. Gas sources

The accumulation of gas hydrates is dependent on the presence of gas, which is derived from hydrocarbons sourced from a variety of geological origins. The exploration of oil and gas in the South China Sea has revealed that conventional oil and gas in this region are primarily derived from thermogenic gas generated in deep rocks. Theoretically, under low-temperature and high-pressure conditions required for the formation of NGHs, any gas can be used as a gas source for the formation of NGHs deposits. Currently, hundreds of oil and gas fields have been discovered in the Cenozoic strata in the South China Sea, and the majority of these fields are gas fields. These include both shallow and medium/deep oil and gas fields, which are connected to biogenic gas developed in the shallow region and thermalgenic one developed in the medium/deep region of the South China Sea, providing a plentiful supply of gas for the accumulation of gas hydrates (Kang YZ, 2021). Exploration of NGHs deposits discovered around the world has also demonstrated that the gas involved in the formation of NGHs originates from biogenic gas and pyrolytic gas, and the thermogenic gas includes both oil-type gas and coal-bed gas (Fig. 2; Dai JX et al., 2017).

Microbial natural gas is formed via the decomposition of organic matter by microorganisms, and there are two primary sources: carbon dioxide reduction and fermentation. In carbon dioxide reduction, the natural gas generated via this process is the primary source of microbial gas. The carbon dioxide involved in the reduction process to produce natural gas is primarily derived from *in situ* oxidation and decarboxylation of organic matter. Therefore, the presence of a substantial quantity of organic matter is crucial for the formation of microorganisms.

Thermogenic methane is a product of the thermal evolution of organic matter. During the initial stages of maturation, thermogenic methane is generated in conjunction with other hydrocarbon and non-hydrocarbon gases, frequently in conjunction with crude oil. At the highest degree of thermal evolution, the C-C bonds in kerogen, bitumen, and crude oil are broken, resulting in the production of methane. The degree of maturity increases with increasing temperature, and each type of hydrocarbon has a specific thermal window that is most conducive to its formation. Methane is primarily generated at a temperature of 150°C (Tissot BP and Welte DH, 2013; Wiese K and Kvenvolden K, 1993).

The exploration practice in the South China Sea indicates

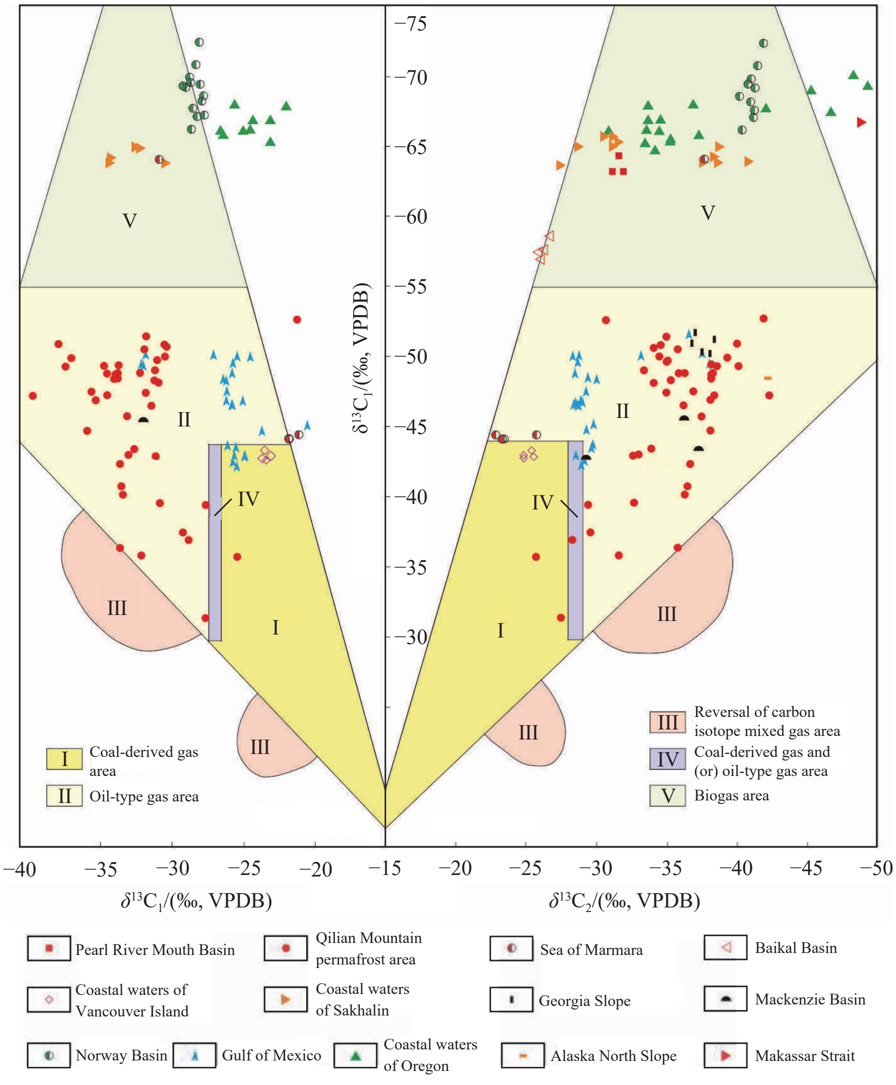

Fig. 2. Gas sources of discovered gas hydrates in the world (modified from Dai JX et al., 2014).

that the gas source of gas hydrate formation in the Shenhu area is primarily biogas, and that in the local area has a thermal origin. A significant proportion of gas hydrate formation in the Qiongdongnan Basin is attributed to thermogenic gas, whereas in the Dongsha area, it is characterized by both biogas and thermogenic gas.

2.2. Gas migration

The migration of natural gas is a necessary condition for the accumulation of NGHs. The microbial gas generated in the shallow subsurface is insufficient to support the formation of high-abundance gas hydrate deposits. Furthermore, the gas hydrate stability zone is not buried deep enough to form thermogenic natural gas. The formation of an NGHs reservoir necessitates the establishment of an effective communication pathway between the gas source and reservoir through gas migration (Lüdmann T and Wong HK, 2003).

Two principal modes of gas hydrate migration have been identified in the South China Sea. (1) The first is free gas phase diffusion and water-soluble gas phase migration, which occurs in a water medium. Migration via diffusion is an inherently slow process. For instance, a considerable number of diffused hydrates developed in Shenhu area have migrated and formed reservoirs in this manner. (2) The second is independent migration of gas phase migration. The migration of natural gas through water-soluble gas or independent gas-phase convection must be achieved through effective migration channels, and the main gas hydrate gas migration channels in the South China Sea mainly include faults, gas chimneys, highly permeable layers, and other similar structures (He LJ et al., 2011; Wu SG et al., 2010). Among these channels, faults are the primary pathway for the vertical migration of hydrocarbon gases to the hydrate stability zone (Zhong GJ et al., 2022). Cracks and fissures, such as gas chimneys, extend the flow range of hydrocarbon gases (Sun YB et al., 2012). The tilt and fracturing of the lateral and top sedimentary layers caused by the formation of mud diapirs can accelerate the upward migration of deep gas. The high permeability layer also serves as a conduit for high-flux fluid migration. For instance, the seepage hydrates that are developed locally in the Qiongdongnan area migrated locally to form highly saturated hydrates through faults and mud diapirs. In the Dongsha area, gas hydrates have formed at the bottom of the stable region through diffusion, faults, and a high permeability layer, while seepage hydrates have formed in the upper part of the stable region (Song HB et al., 2001; Su PB et al., 2017b). Consequently, the South China Sea contains a multitude of migration and transport channels for gas hydrate accumulation, including fractures, diapirs, gas chimneys, and high permeability layers. These channels spatially combined into a composite migration system (Fig. 3).

2.3. Natural gas hydrate reservoir formation

The reservoir is the space where gas hydrates accumulate. The formation of NGHs is primarily influenced by the temperature and pressure conditions. These deposits can be found in any range of the temperature-pressure stability region (Fig. 4) under adequate gas sources. In contrast, conventional oil and gas are strictly controlled by traps and have a relatively limited distribution. In the pressure range of NGHs stability, the types of gas hydrate reservoirs include sand, silt, and silty sand, and the reservoir spaces include pores, fractures, and caves. The production modes are diverse.

The three most common forms of gas hydrates in marine areas are pore-filling, fracture-filling, and compound gas hydrates (Holland ME et al., 2008; Liang JQ et al., 2016). Specifically, pore-filling gas hydrates are mostly prevalent in the pores of coarse sand sediments with high permeability, which are the result of the diffusion of gas or dissolved gas fluid from the bottom to the upper sediments, such as the diffused hydrates formed in the Shenhu area. fracture-filling gas hydrates are more prevalent in silty sand sediments with small granular pores. This type of hydrate is formed in the form of a mass, nodules, lens, or veins within cracks in the sedimentary layer. The seepage gas hydrates found in the Qiongdongnan basin are predominantly of this type. Compound hydrates are a combination of the two aforementioned types, and the majority of the hydrates formed in the Dongsha area belong to this category (Liu CL and Sun YB, 2021).

3. Characteristics of natural gas hydrate deposit reservoirs

A comprehensive understanding of the characteristics of gas hydrate reservoirs is essential for the accurate evaluation

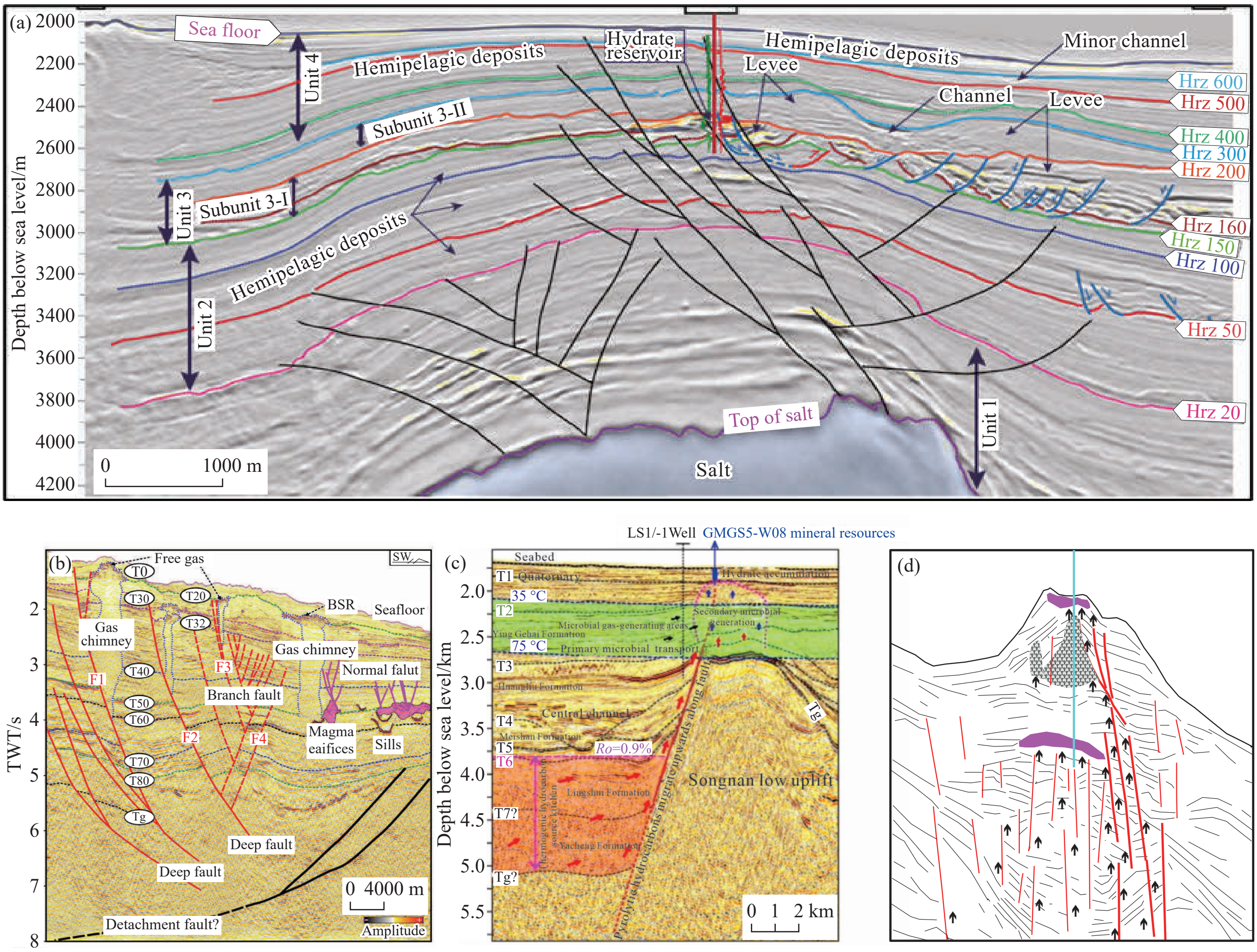

Fig. 3. Gas migration channels of natural gas hydrate. a–the migration channel composed of the fault and diapir in the hydrate zone of the Gulf of Mexico; b, c and d–the migration channels composed of the fault, diapir, and gas chimney in the Shenhu, Qiongdongnan, and Dongsha area, respectively.

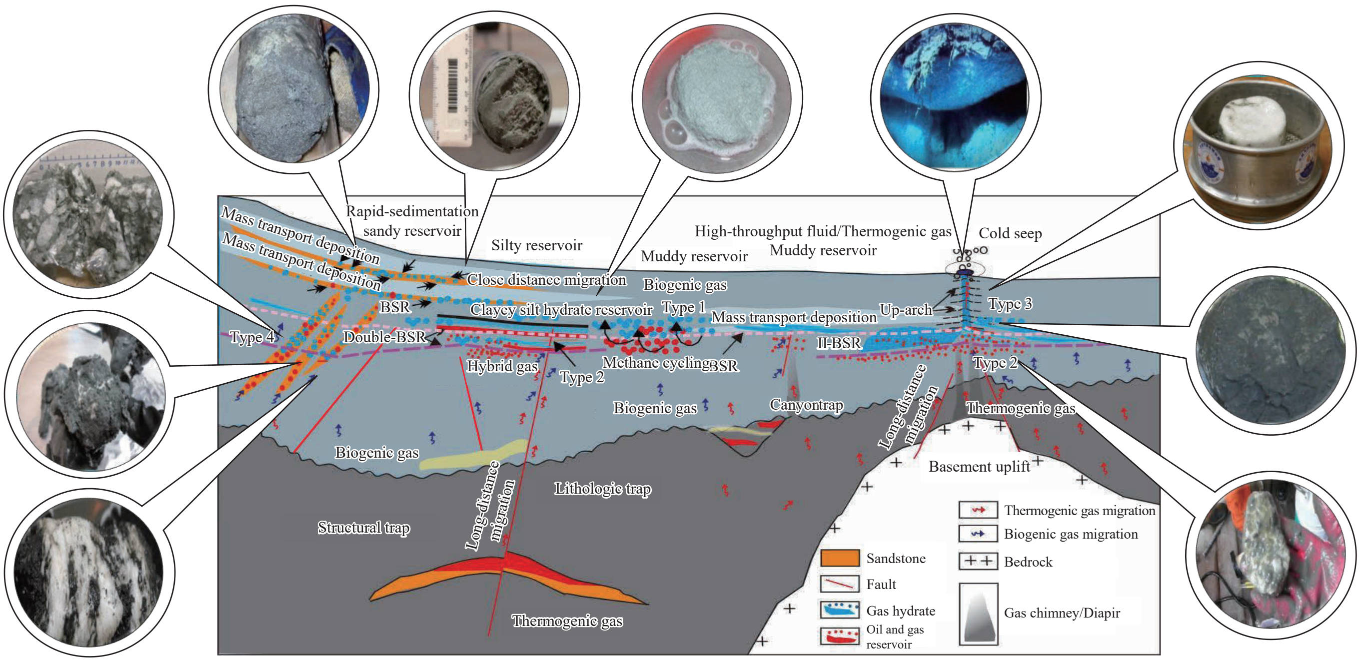

Fig. 4. Gas hydrate storage and production modes in different reservoir types within the stability zone.

of their resources (Liu CL and Sun YB, 2021). Factors such as the sediment type, reservoir space availability, and heterogeneity of gas hydrate reservoirs influence the growth and spatial distribution of gas hydrates to a certain extent. Different types of gas hydrate reservoirs often exhibit distinct hydrate occurrences and even exert control over the distribution and enrichment characteristics of gas hydrates. Ultimately, fundamental physical properties such as the acoustic properties, electrical properties, mechanical properties, and permeability of the reservoir are affected (Zhong GF et al., 2021).

3.1. Classification of gas hydrate reservoirs

3.1.1. Pore-filled hydrate reservoir

A pore-filling hydrate reservoir refers to the gas hydrate enrichment layer in the sediment pores in the form of suspension, contact, and coalescence. These reservoirs are formed via *in situ* migration of biogenic methane or deep thermogenic methane gas into the pore space of the shallow surface sediments on the seabed through diffusion, and they are mainly distributed in deep-water sediments such as submarine fans, waterways, natural levees, and turbidity deposits. Most of these reservoirs are located within the gas hydrate stability zone, such as the turbiditic rocks and channel systems in the large ancient river system around the Black Sea (Haeckel M et al., 2015), the Gulf of Mexico (Collett TS et al., 2012), and the Nankai Trough in Japan (Komatsu Y et al., 2015). In addition, in some silty sediments that are rich in foraminifera shells, diatoms, and pyrite, hydrates often exist in biological shells in the form of pore-filling hydrates due to their high porosity and permeability and are generally distributed in diffusion-like manner in continental margins (Su X et al., 2005), such as the Black Sea (Ginsburg G et al., 2000), the Shenhu area(Wang XJ et al., 2014b), and the Gulf of Mexico (Portnov A et al., 2020).

3.1.2. Fracture-filled hydrate reservoir

In silty silt deposits with small granular pores, hydrates can only occupy fractures of different shapes and sizes and occur in block-shaped, vein-shaped, and nodular forms. This is because it is difficult for hydrates to fill the pores of fine-grained sediments, which results in the formation of hydrate reservoirs of multiple deposit types. Fracture-filling hydrates typically utilize a high-flux fluid to facilitate the transport of deep hydrocarbon gas into fracture channels, including diapirs, fractures, and fracture zones. This process results in the formation of relatively dense vein, layer, and/or block gas hydrates in the shallow surface layer of the seabed (Tréhu A et al., 2006; Winters WJ et al., 2014), such as the hydrate ridge area in the Cascadia continental margin (Tréhu AM et al., 2003), the Krishna-Godavali Basin (Gullapalli S et al., 2019; Kong X et al., 2019), and the Qiongdongnan Basin (Fan Q et al., 2024; Hu WR et al., 2010).

3.1.3. Compound hydrate

Compound hydrate deposits are a complex reservoir-forming system composed of pore-filling hydrate layers developed at the bottom of the stability zone and fracture-filling hydrates developed in the upper part of the stability zone. Not only can be enriched in fine sediments pores, but also fill in the fractures, thus exhibiting characteristics of both pore- and fracture-filling hydrates, which are indicative of a reservoir-forming system, such as that in the Dongsha area (Liang JQ et al., 2016).

3.2. Sediment properties of natural gas hydrate reservoirs

Marine gas hydrates are primarily located in the pores and/or fractures in unconsolidated sedimentary layers, such as Neogene and Quaternary strata, which are composed of various types of sediments, including sand, silt, clay silt, and silty clay (Liu CL and Sun YB, 2021). The saturation of marine gas hydrates is primarily influenced by the characteristics of the reservoir's lithology, pores (or fractures), and methane flux.

3.2.1. Lithology of different hydrate reservoirs

High-saturation NGHs typically accumulate in the layer characterized by coarse sediment particles and large pore spaces, such as turbidity sediments and sand layers. These formations exhibit features of high porosity and high permeability, which facilitate the migration and accumulation of hydrocarbon-bearing fluids (Horozal S et al., 2015). The grain size of the reservoir sediments has a significant effect on the classification of the sedimentary layers, pore size, and properties of the pore water. Furthermore, it influences the gas hydrate phase equilibrium condition, which is an important parameter for characterizing the degree of hydrate enrichment (Ito T et al., 2015; Zhang H et al., 2016). Additionally, silty sediments rich in foraminifera and calcareous fossil particles, such as bio-carbonate rocks, diatom fossils, and volcanic ash, can facilitate gas hydrate accumulation due to pore structure changes (Liu CL and Sun YB, 2021).

Pore-filling hydrate reservoirs, represented by those in the Shenhu area, are predominantly composed of clay silt and/or silty clay that are rich in foraminiferous fossils. The sediment components are primarily clastic minerals, clay minerals, and carbonate minerals, among which the contents of quartz and feldspar are high (Fig. 5). The compound hydrate reservoir in the Dongsha Sea area is dominated by fine-grained clay silt containing fractures, and its sediment composition is similar to that in the Shenhu area. In contrast, the clastic minerals in the fracture-filling hydrate reservoir sediments in the Qiongdongnan Basin are relatively simple, comprising primarily calcrete bioclasts and locally enriched pyrite and quartz, as observed at station W01B-18(Fig. 6).

3.2.2. Characteristics of Methane flux in different hydrate reservoirs

The differences in the occurrence of gas hydrates depend on the pore space of the reservoir and are closely related to fluid migration (Tréhu A et al., 2006). A low-flux methane fluid diffuses slowly, and the gas hydrates formed in relatively coarser sandy sediments or fractures have a higher saturation degree. For example, the saturation degree of the hydrates filling thick layer saturation pores found in the Shenhu area can reach 76% (Ge JW et al., 2023). However, in areas with a high methane flux (strong leakage area), the controlling factor of the lithology on hydrate reservoirs is relatively weak, and even clay with a low permeability can become highly saturated gas hydrate reservoirs depending on the gas pressure, such as the fracture-filling hydrates

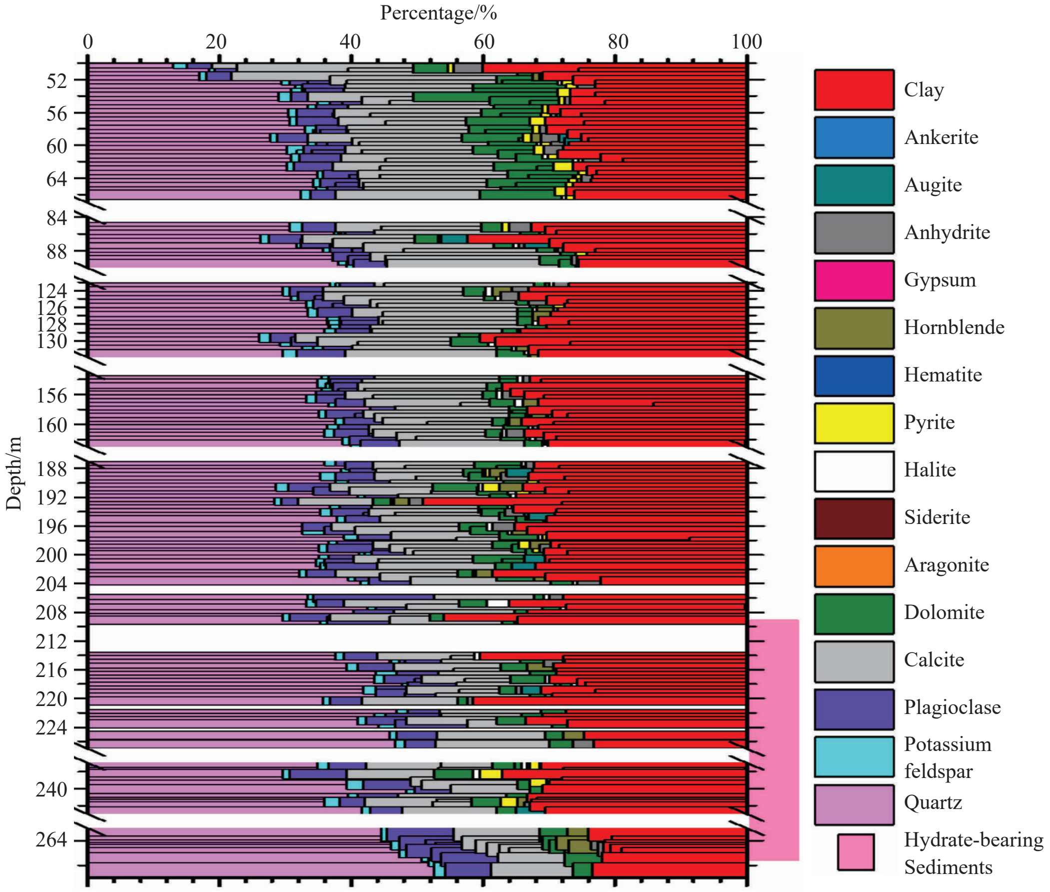

Fig. 5. Variation of sediment components at station W17B in Shenhu area.

discovered in well W08 in the Qiongdongnan basin. Hydrates mainly fill sediment fractures or relatively coarse-grained fine siltstone, and the hydrate saturation degree is medium to high (3%–54%) (Fan Q et al., 2024; He YL et al., 2022).

3.3. Seismic response characteristics of natural gas hydrate reservoirs

The seismic response of gas hydrate reservoirs are controlled by the difference in the wave impedance between the hydrate deposit and the underlying layer, and the amplitude, continuity, and frequency characteristics are closely related to the formation porosity, hydrate concentration, and free gas characteristics. The geophysical markers of pore-filling hydrates mainly include bottom-simulating reflection markers, amplitude markers, velocity markers, and amplitude versus offset markers (Fig. 7; Su PB et al., 2020; Wang XJ et al., 2014b). Thus, fracture-filling hydrates should be combined with stability region analysis to enable fine attribute analysis of the fracture system (Fig. 8; Rai N et al., 2020).

3.4. Log response characteristics of natural gas hydrate reservoirs

There are obvious similarities between NGHs and ice (Gabitto JF and Tsouris C, 2010). The densities of both NGHs and ice are less than that of water, and the densities of NGHs and ice layers are less than those of similar water layers. When the NGHs cage is filled with methane, the density decreases. Therefore, a sharp decrease in the log density may reflect the presence of gas hydrates or massive gas hydrates.

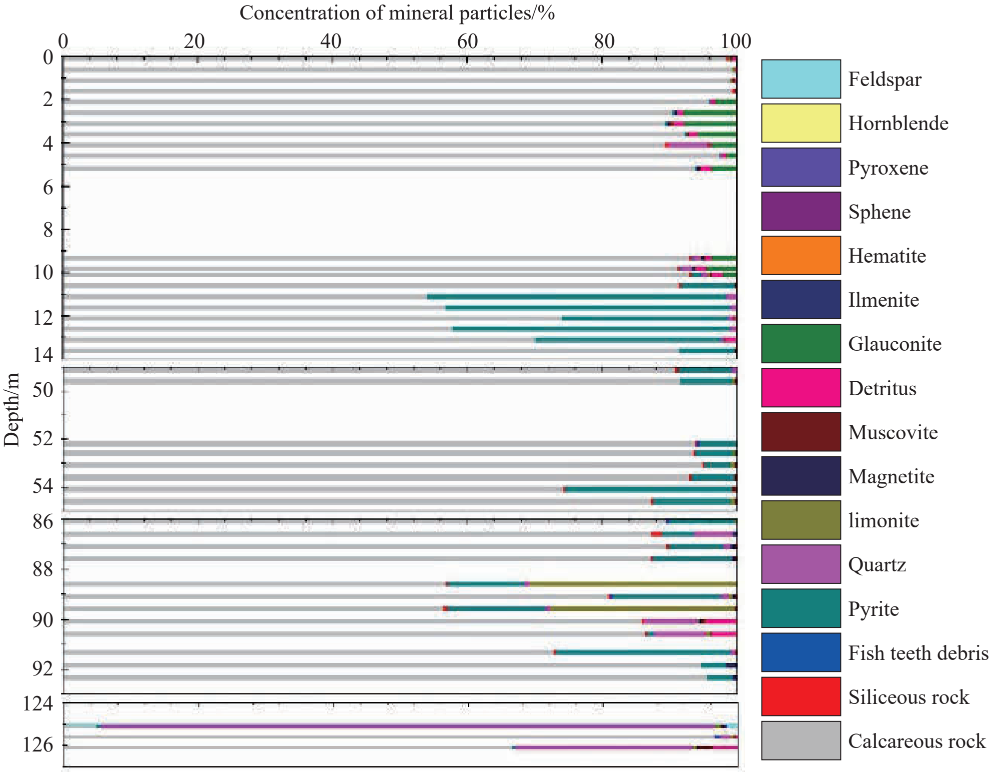

Fig. 6. Variation of detrital mineral species and content at station W01B-18 in Qiongdongnan area.

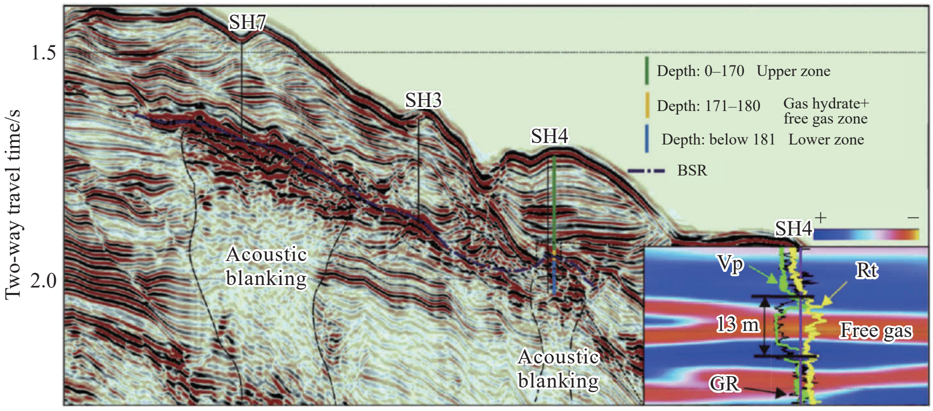

Fig. 7. Seismic response characteristics of pore-filled hydrate (modified by Wang XJ et al., 2014b).

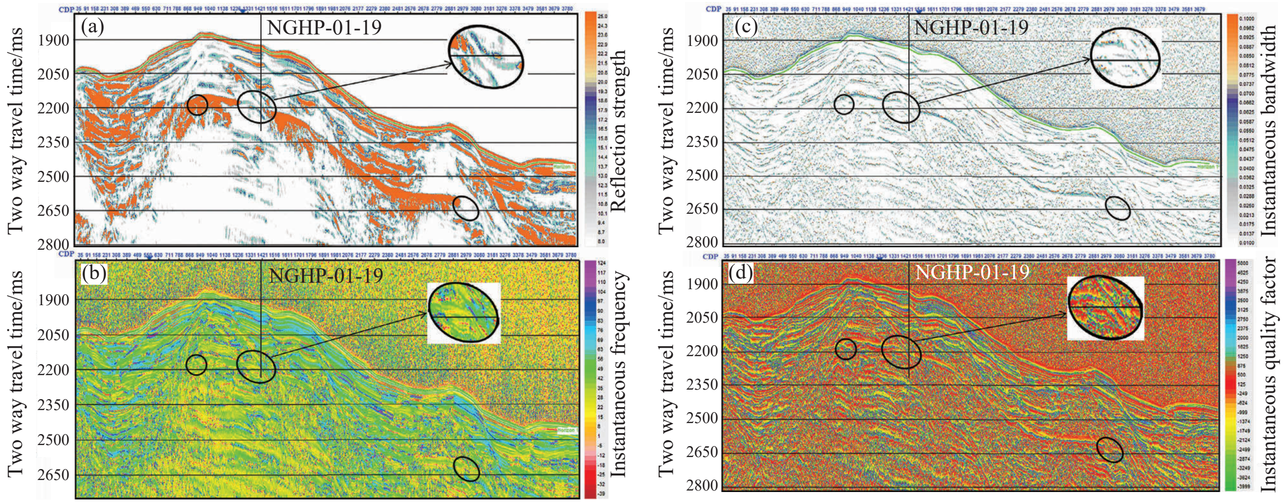

Fig. 8. Seismic response characteristics of fracture-filled hydrate (modified from Rai N et al., 2020). a–Seismic attribute of reflection strength for seismic line; b–instantaneous frequency attributes of seismic line; c–instantaneous bandwidth attributes of seismic line; d–instantaneous quality factor attribute of seismic line.

In addition, gas hydrate-bearing reservoirs tend to exhibit a relatively high acoustic transmission velocity, resistivity, neutron porosity, and low response values in natural gamma (GR) well measurement curves (Liang JQ et al., 2017; Ning FL et al., 2013). This is because the P-wave velocity of pure NGHs (3.3–3.6 km/s) is much higher than that of water (approximately 1.6 km/s); similar to ice, NGHs are insulators, and the resistivity value will increase significantly when the reservoir contains NGHs. In addition, the formation of gas hydrates in a reservoir is accompanied by increases in the amounts of carbon and hydrogen in the pores containing methane, and there is no radioactive element precipitation in this process. Thus, the neutron log response data depend on the number of hydrogen atoms per unit volume and increase accordingly, and the GR log response has low values.

3.4.1. Pore-filled hydrate reservoirs

Pore-filling hydrate occurrence intervals are generally characterized by low compaction degree and good porosity and permeability conditions (Kang DJ et al., 2024). Taking well SH7B in the Shenhu area as an example, the hydrates are dispersed and disseminated in underconsolidated sediments that are rich in foraminifers and calcareous nanofossils. The average porosity of the hydrate-bearing layers is 44.97%, which is slightly higher than that of the overlying layers, and the mudstone content is significantly lower than that of the overlying layers. High porosity, high permeability, and low mud content are typical characteristics of favorable gas hydrate reservoirs, and these properties manifest in logging curves as high resistivity and high wave velocity values (Fig. 9).

3.4.2. Fracture-filled hydrate reservoirs

Taking the Qiongdongdong Sea area as an example (Fig. 10), the results of logging during drilling at station W08-2018 showed that fracture-filling hydrates have developed at 7.61–16.61 m, 21.61–52.41 m, and 57.61–178.11 m below the seafloor and that the high resistivity of the hydrate layer is abnormal. The maximum resistivity can reach 67.55 Ω·m, and the overall gamma-ray value is low. In addition, relatively dense mass flow deposits play a certain role in capping a formation containing fracture-filling hydrate reservoirs.

3.4.3. Compound hydrate reservoirs

Compound hydrate reservoirs are found in the Dongsha area, and the deep hydrate layer at the bottom of the stability zone contains uniformly distributed pore-filling hydrates, which are evenly distributed in silty clay. The hydrates in the local layer coexist with biodetrites such as carbonate rocks and shells. Moreover, in the shallow layer, the hydrates occur as veins and nodules, and there are obvious gas leakage channels in the seismic section, with typical characteristics of fracture-filling type hydrates (Liang JQ et al., 2016). Taking station W16 as an example, the maximum resistivity and maximum acoustic velocity of the layer are 3.36 ohm.m and 2770 m/s, respectively, in the 193.49–203.19 m depth interval below the seafloor. In addition, high saturation dispersed hydrate samples have been obtained from the 200–203.5 m depth interval via drilling. In a field test, the hydrate saturation of the pressurized core was as high as 44%–55%. In contrast, in the shallow layer, the hydrates occur in the forms of veins and nucleation, and there are obvious gas leakage channels in the seismic section. The logging resistivity and acoustic velocity of this section also increase significantly. The acoustic velocity reaches 1600–2800 m/s, and the resistivity exceeds 10 ohm.m (Fig. 11).

4. Evaluation methodology of clathrate hydrate resources

According to the basic principle and applicability of evaluation methods, the current evaluation methods of NGHs resources mainly include the volumetric, genesis, and analogical methods.

4.1. Volume method

Because *in-situ* NGHs occur in the solid state, which is

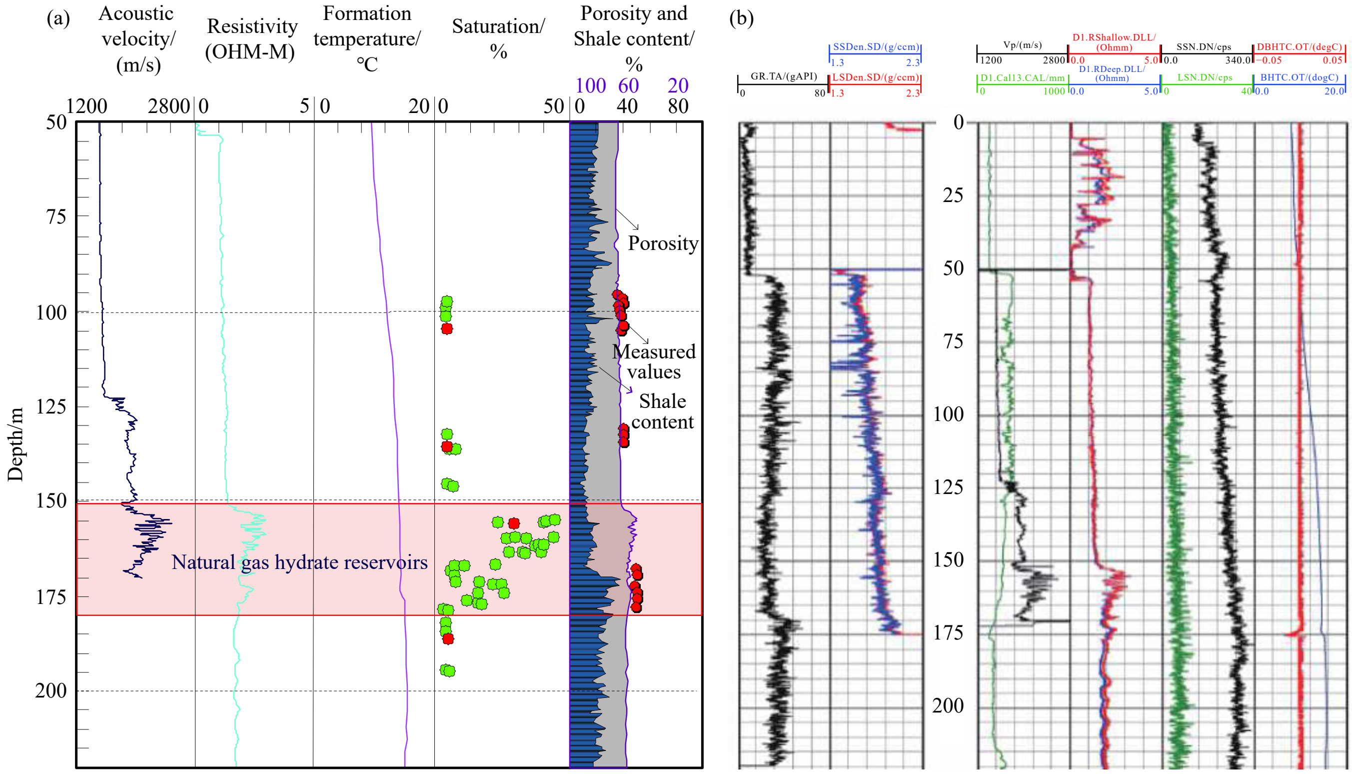

Fig. 9. Distribution and logging characteristics of gas hydrate reservoirs at SH7 station in Shenhu area.

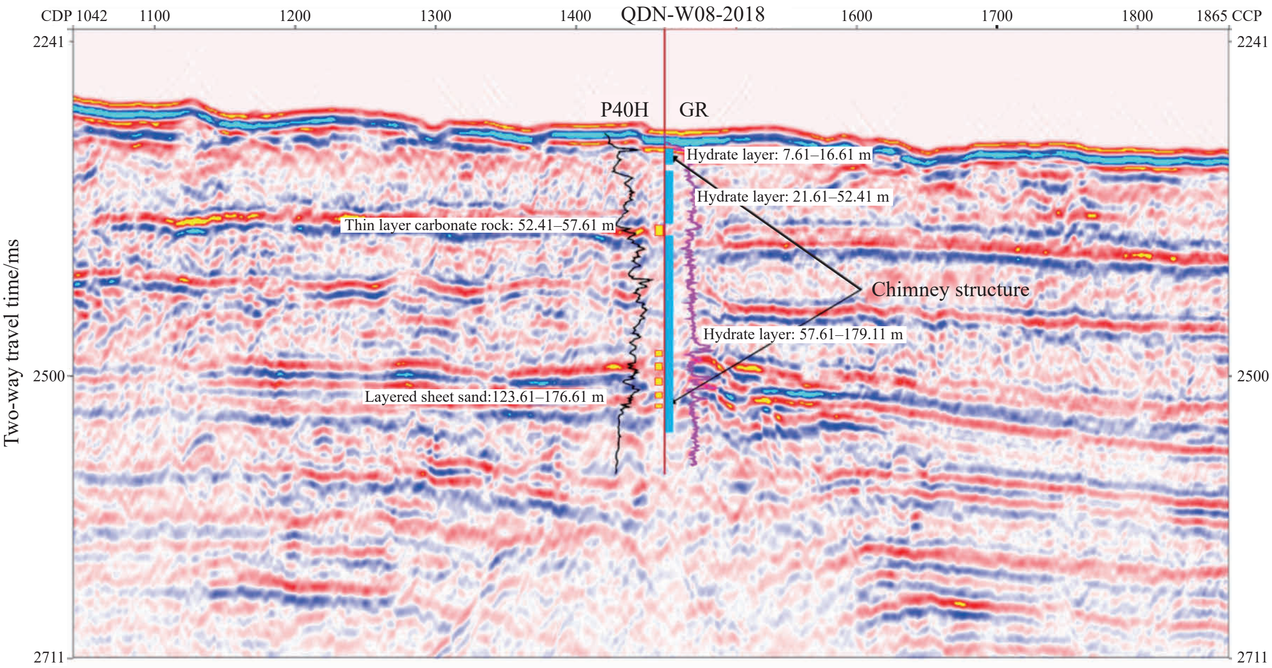

Fig. 10. Seismic profile and LWD curve at station W08-2018 in the Qiongdongnan Sea area.

quite different from the state of conventional natural gas in a reservoir, the volumetric method is more suitable for the calculation of NGHs resources, and it is also one of the most widely used methods for the evaluation of NGHs resources. For the prospective area delineated in the early stage of exploration, the volumetric method based on the Monte Carlo algorithm can evaluate the resource potential in a more scientific and reasonable way. For more mature exploration areas, it is better to accurately evaluate the resources of gas hydrate ore bodies using the volumetric method based on 3-D geological modeling (Fig. 12).

4.1.1. Basic principles

Based on the static characteristics of natural gas clathrate hydrates, the volumetric method is used to establish the linear relationships between the number of resources and the

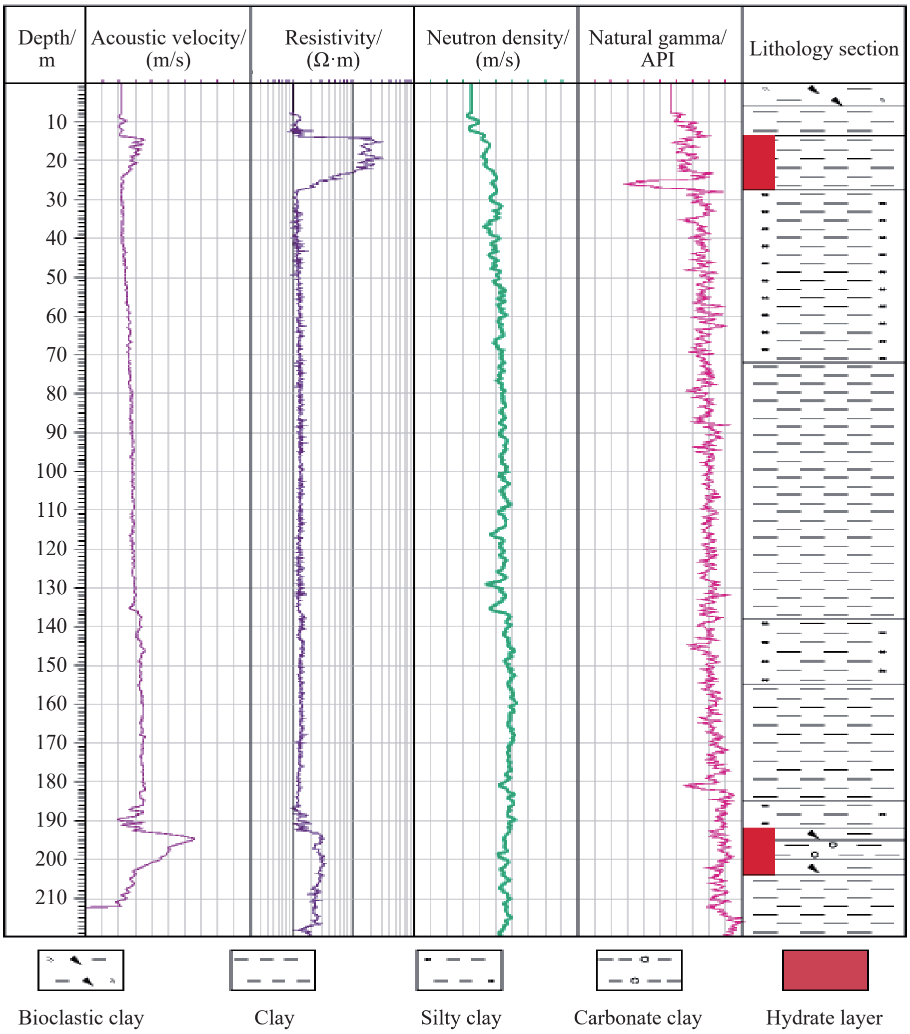

Fig. 11. Well logging curve of W16 station and distribution map of hydrate layer in Dongsha area (modified from Liang JQ et al., 2016).

reservoir parameters and to calculate the number of resources. The mathematical formula is as follows:

$$Q_h=A_h\times Z_h\times \Phi\times S_h\times E,$$

where Q_h is the NGHs resources (m^3); A_h is the effective area of the reservoir (m^2); Z_h is the effective thickness of the reservoir (m); Φ is the porosity; S_h is the hydrate saturation; and E is the gas production factor.

4.1.2. Main parameters

The following five key parameters are considered in the calculation of the amount of gas contained in submarine gas hydrate reservoirs: (1) The distribution area of NGHs; (2) the thickness of the gas hydrate reservoir; (3) the porosity of the reservoir sediments; (4) the saturation of the clathrate hydrates in the reservoir sediments; and (5) the production factor of the gas hydrates (under the standardized state). The actual gas hydrate resources are the product of these five parameters; therefore, the methods for quantitative evaluation of submarine gas hydrate resources via the volumetric method (conventional volumetric method based on simple algebraic operations and the Monte Carlo method based on probabilistic statistical calculations) essentially involve the estimation of these five parameters and the calculation of the product of these five parameters.

Thus, the accuracy of gas hydrate resource evaluation mainly depends on the means of attainment, accuracy, and reliability of the above five parameters. According to the means of obtaining the parameters in the actual exploration process, the methods of selecting parameters for NGHs resource evaluation can be categorized into three main types: similar analogy methods, indirect measurement methods, and direct measurement methods. Different parameter selection methods are applicable to different degrees of exploration stages, and the resource evaluation results obtained have different accuracies.

(i) Similarity analogy method

In the initial stage of an NGHs survey, the distribution of the NGHs resources is usually calculated using the range of the NGHs stability zone due to the lack of actual parameter measurement data, or it is determined using the ranges of the distributions of physical and chemical prospecting anomalies. Based on the assumptions that similar mineralization backgrounds and metallogenic conditions may result in the output and distribution of minerals of a similar scale, reservoir parameters such as the porosity, saturation, and gas

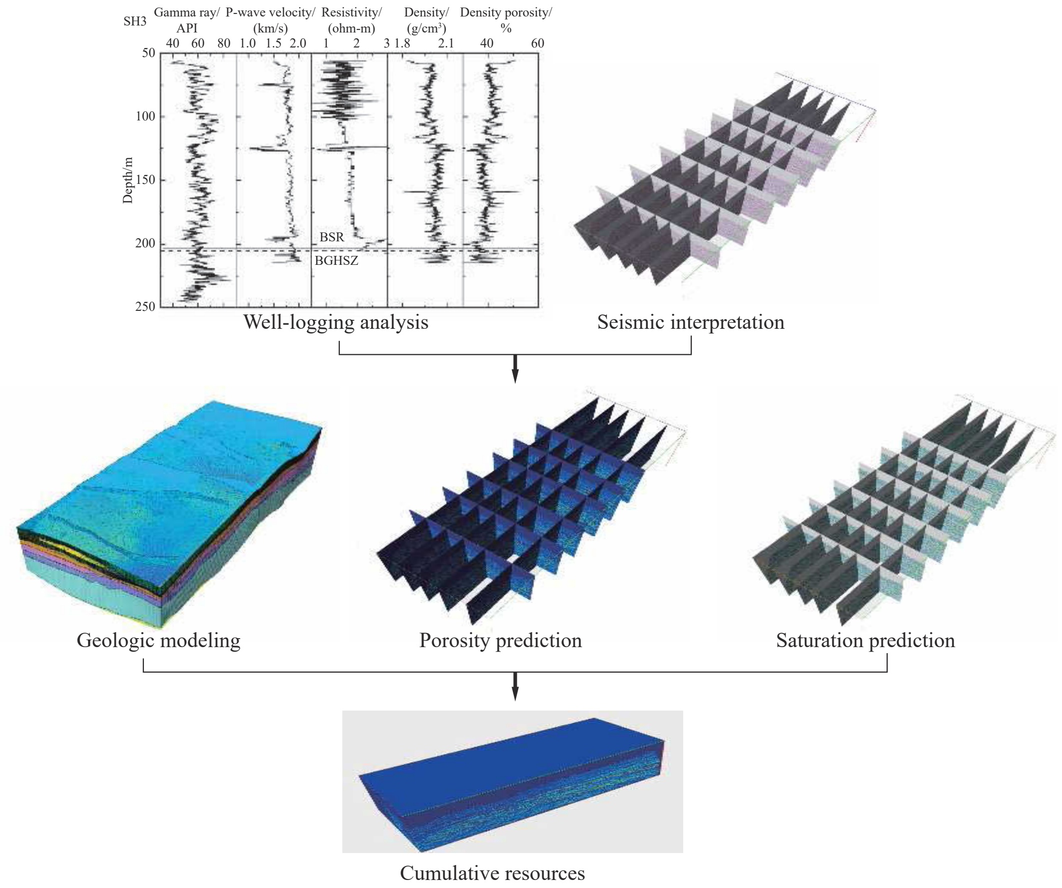

Fig. 12. Volume method for the evaluation of resources.

production factor for resource evaluation are selected mainly through analogy to the actual measured parameter data for areas with similar ore-forming backgrounds and mineralization conditions.

(ii) Indirect measurement method

During the general survey of clathrate hydrates, the relevant evaluation parameters are calculated and selected using geophysical and geochemical methods. The geophysical methods mainly use seismic data interpretation to determine the distribution range of the gas hydrates, reservoir thickness, reservoir porosity, and gas hydrate saturation. In addition to seismic data, seafloor electromagnetic data (Edwards RN, 1997) and resistivity logging data (Collett TS, 1999; Hyndman RD et al., 1999) are also used to estimate the relevant parameters of the seafloor gas hydrate reservoir. The geochemical method involves estimating the saturation of the clathrate hydrates in the pore space of sediments using the chloride ion (Cl^-) concentration anomaly or oxygen isotope (Δ^{18}O) anomaly of the pore water. Geochemical indices such as the sulfate gradient of the pore water and the chloride ion concentration anomaly in shallow sediments can also be used to indicate the existence of clathrate hydrates and to delineate the range of these clathrate hydrates.

(iii) Direct measurement method

In the detailed investigation stage of NGHs, data from logging and pressure-holding coring wells are used to directly calculate the saturation of NGHs and other key parameters. This is the most direct and effective method for calculating gas hydrate resources, but it is only applicable in the stage with a high exploration degree, and it requires that sufficient logging and pressure-holding coring wells be constructed. Compared with the analogical and indirect methods, the resource evaluation results of the direct measurement method have been greatly improved in terms of accuracy.

4.1.3. Applicability

The volumetric method is applicable to a wide range of hydrate reservoir types and can be used for different reservoir types. It is also applicable to all stages of gas hydrate exploration. In the early stage of prospect evaluation, the Monte Carlo-based volumetric evaluation method is the most scientific and reasonable, while in the later stage of ore body evaluation when the degree of exploration is more mature, the volumetric method based on geological modeling yields the most accurate results. It should be noted that for the resource evaluation of large, uniformly distributed, pore-filling hydrates, the spatial distribution of hydrate reservoirs in sediments with different lithologies can be roughly described. However, for fracture-filling hydrates, it is difficult to define the key reservoir parameters, such as the hydrate saturation, due to the strong non-homogeneous nature of the reservoirs and the lack of obvious geophysical response characteristics.

4.2. Genesis

Because the main gas sources of NGHs formation are biogenic and thermogenic gas, the current evaluation of the genesis method mainly adopts basin numerical simulation technology to simulate the generation, migration, and accumulation of biogenic gas and thermogenic gas and ultimately to determine the NGHs resources in the evaluation area (Fig. 13).

4.2.1. Fundamentals

Starting from the dynamic aggregation process of NGHs, the gas production, venting, and aggregation volumes are predicted based on the hydrocarbon system theory, and the gas resources cemented by hydrates in the stability zone are calculated through combination with the phase equilibrium theory of NGHs.

4.2.2. Evaluation parameters

The genesis method integrates the distribution and characteristics of the actual geological body into a mathematical model based on the geological model and quantifies the basic conditions required for the formation of the hydrate system into the initial conditions of the geological model using the boundary model. Then, the genesis method combines the hydrocarbon generation and discharge model to simulate the generation process and transport characteristics of the gas in the hydrate system and calculates the parameters of the gas source such as gas production, gas discharge, and aggregation. Finally, the genesis method simulates the amount of gas resources that are solidified by the gas into the stability zone after the gas enters the stability zone using the hydrate aggregation model. The hydrate aggregation model is used to simulate the amount of gas resources cemented by hydrates after the gas enters the stability zone. The corresponding evaluation parameters mainly include the geological model parameters, boundary condition parameters, gas content parameters, and phase equilibrium parameters. The geological model parameters include fault characteristics, stratigraphic distribution, and lithology, which are used to characterize the fluid transport conditions and effective storage space and are obtained using fault body engraving techniques, stratigraphic interpretation, and core sample determination. The boundary condition parameters include paleotemperature, paleo-thermal flow, and paleo-bathymetry data, which characterize the environmental conditions required for the evolution of the hydrate system and are predicted using paleotemperature scale analysis, tectonic-thermal evolution analysis, and equilibrium profile restoration techniques. The gas content parameters include the gas components, organic matter content, and maturity, which reflect the gas source conditions for hydrate formation and are obtained using the specular reflectivity test, seepage mechanics analysis, and fluid potential analysis. The phase equilibrium parameters include the present temperature, pressure, and salinity, which characterize the conditions for stable hydrate aggregation and are obtained using gas component analysis, hydrate generation kinetic experiments, and calibration of field measurement data.

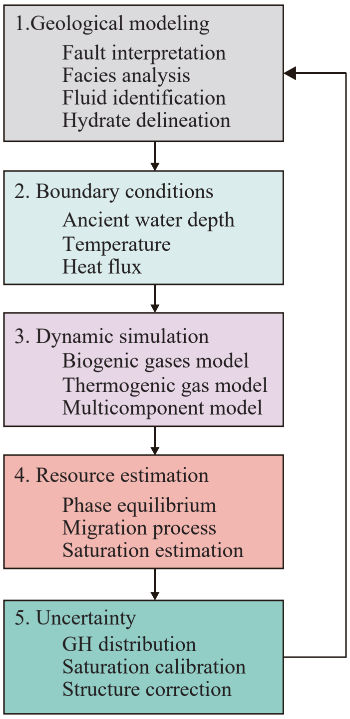

Fig. 13. Genetic method for the evaluation of resources.

4.2.3. Applicability

The genesis method has a simple principle, and the geological significance of the parameters and results is clear, but the modeling work requires the support of abundant basic research work. It is suitable for large-scale comprehensive evaluation without considering the hydrate accumulation mode. The model describes the vertical non-homogeneity using single station data and controls the lateral non-homogeneity using temperature, pressure, and lithology data. However, it cannot clarify the scale of the pore-filling and fracture-filling hydrate reservoir, and it is difficult to formulate a targeted exploitation plan based on the results. The accuracy and precision of the evaluation results are limited by the degree of hydrate exploration and research, and the results has a larger uncertainty.

4.3. Analogies

The analogical evaluation method is mainly based on the analogy of the geological conditions of NGHs formation, and it requires the establishment of the scale zone evaluation process on the basis of a full understanding of the regional geological conditions.

4.3.1. Fundamentals

Starting from the similarity of the geological conditions underlying the formation of NGHs reservoirs, the formula for extrapolating the resources of the evaluation area from the known resources in the scale area is as follows:

$$Q_h = A \times a \times P,$$

$$a = \frac{\text{Total geological evaluation score of the evaluation area}}{\text{Total geological evaluation score of the scale area}},$$

where Q_h is the NGHs resources in the evaluation area (m^3); A

is the area of the evaluation area (m^2); a is the similarity coefficient, $0 < a \leqslant 1$; and P is the abundance of the NGHs resources in the scale area (m^3/m^2).

4.3.2. Evaluation parameters

The analogical method is based on the degree of similarity between the hydrate formation conditions in the scale area and the evaluation area, and the gas resources in the evaluation area are calculated from the hydrate resources in the subsurface space corresponding to the unit area of the scale area. The main evaluation parameters include evaluation unit area, similarity coefficient, and resource abundance of the scale area. The area of the evaluation unit is the same as that of the volumetric method, and the similarity coefficient is based on the evaluation indices and assignment standard established based on the scale area. The score of the corresponding indices of the evaluation unit is determined by adopting the subjective/objective weighting method, and the resource abundance in the scale area is obtained using the volumetric method to calculate the quantity of the resources corresponding to the unit area of the well control area. The scale area should follow the principle of three highs, i.e., a high exploration degree, a high understanding of the geological laws, and high resource potential. In addition, the evaluation indices must be based on evidence and reasonable parameters (Sun YB et al., 2020), which must at least include the gas source conditions, transportation conditions, aggregation conditions, and formation conditions (Fig. 14).

4.3.3. Applicability

The analogical method is suitable for rapid evaluation in the pre-exploration stage, the parameters are mostly based on qualitative or low-precision measurement data, and the basic geological conditions of the scale area are highly consistent with the evaluation results of the area. Furthermore, the analogical method is relatively reliable, with a low degree of error.

5. Progress in understanding the potential of global natural gas hydrate resources

The correct evaluation of global NGHs resources is particularly important for clarifying the status of NGHs in global resources and the environment. Currently, according to the degree of exploration and current level of understanding, different scholars have generally divided the evaluation of global NGHs resources into two stages (Table 1).

5.1. Prospect area evaluation stage

In the 1970s and 1980s, the investigation of NGHs was

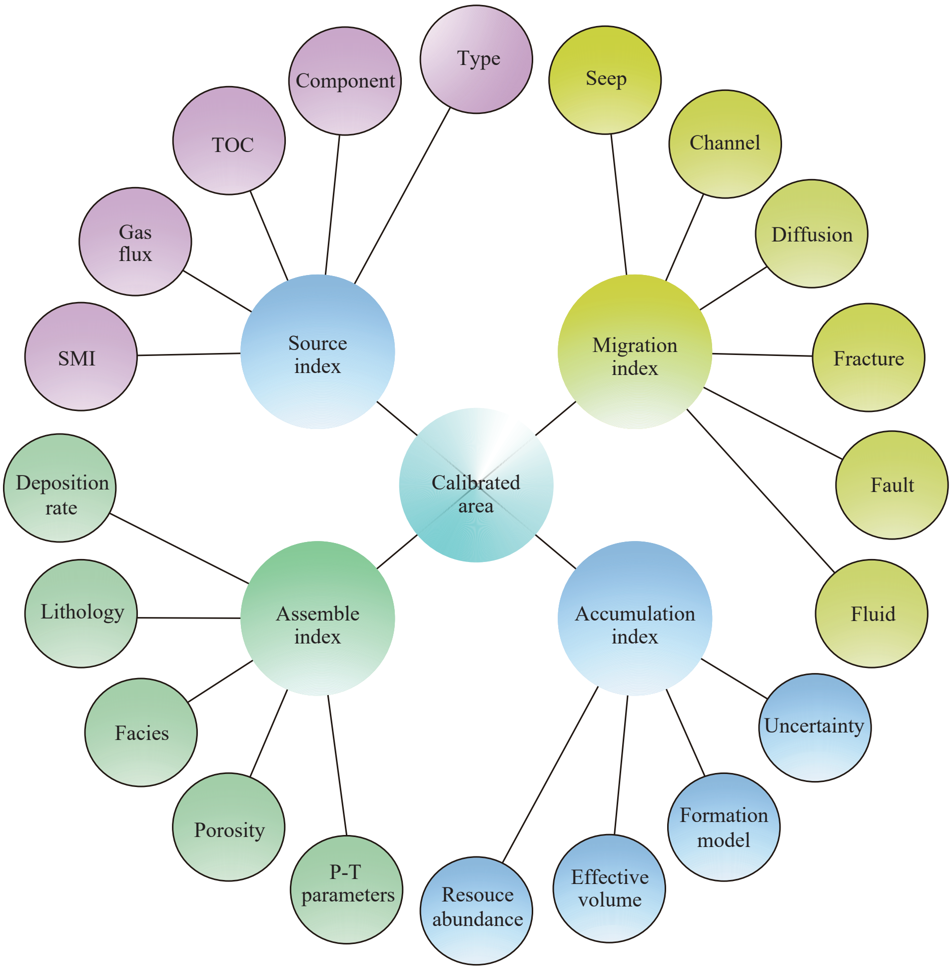

Fig. 14. Evaluation parameters of scale areas.

Table 1. Prediction of natural gas hydrate resources in global sea area.

Evaluation phase	Evaluation method	Terrene ($\times 10^{15}$)	Marine ($\times 10^{15}$ m^3)	References
Perspective evaluation phase	Volumetric method		3021–3085	Trofimuk AA et al., 1973
	Volumetric method		1135	Trofimuk AA et al., 1975
	Volumetric method		1573	Cherskii NV and Tsarev VP, 1977
	Volumetric method		1550	Nesterov I and Salmanov F, 1977
	Volumetric method		110–130	Trofimuk AA, 1979
	Volumetric method	0.031	3.1	Meyer RF and Olson JC, 1981
	Volumetric method	0.057	5–25	Trofimuk AA et al., 1981
	Volumetric method	34	7600	Dobrynin V, 1981
	Volumetric method	0.014	3.1	Meyer R, 1981
	Volumetric method		15	Trofimuk AA et al., 1983
	Volumetric method		40	Kvenvolden KA and Claypool GE, 1988
	Volumetric method		20	Kvenvolden KA, 1988
	Volumetric method	0.74	20	MacDonald G, 1990
	Volumetric method		26.4–139.1	Gornitz V and Fung I, 1994
	Volumetric method		22.7–90.7	Harvey LD and Huang Z , 1995
	Volumetric method		1	Ginsburg G and Soloviev V , 1995
Resource evaluation phase	Volumetric method		6.8	Holbrook WS et al., 1996
	Volumetric method		1.5	Makogon YF, 1997
	Volumetric method	0.1	10	Makogon YF, 1997
	Volumetric method		>0.2	Soloviev V, 2002
	Volumetric method		3–5	Milkov AV et al., 2003
	Volumetric method		1–5	Milkov AV, 2004
	Comprehensive evaluation	0.003	0.28	Boswell R and Collett TS , 2011
	Causal method		0.0082–2.1	Burwicz EB et al., 2011
	Causal method		⩾0.87	Wallmann K et al., 2012
	Causal method		1.05	Piñero E et al., 2012
	Causal method		0.95–5.7	Kretschmer K et al., 2015

not extensively carried out, and it was generally assumed that NGHs were continuously distributed in the stability zone in the sediment layer. The volume method was mainly used to estimate the global NGHs resources. For example, Trofimuk AA et al. (1973), scientists from the former Soviet Union, assumed that NGHs existed in 93% of the ocean and accounted for 100% of the sediment pore volume. They introduced the influences of temperature and pressure on the thickness of hydrate occurrence into this estimation in 1975. The distribution area of gas hydrate accumulation was further reduced, and the gas hydrate resources in the sea area were recalculated to be (110–130)×10^{18} m^3 (Trofimuk AA, 1979).

In the 1980s and mid-1990s, the establishment of the Deep Ocean Drilling Program and the Ocean Drilling Program facilitated a more comprehensive understanding of the distribution of gas hydrates in the oceans. Importantly, hydrate drilling provides a direct basis for the key evaluation parameters of hydrates. In addition to correcting the value ranges of the evaluation parameters, organic carbon critical values (greater than 0.5% or greater than 1%) were introduced to assess the resource potential of NGHs (Kvenvolden KA and Claypool GE, 1988), and the multi-type NGHs were estimated (Gornitz V and Fung I, 1994). The volume of gas in NGHs estimated during this period was approximately 10×10^{15} m^3.

The evaluation stage of the prospect area has undergone a lengthy evolution, progressing from the initial availability of survey data to the subjective selection of parameters, subsequently to objective analogy, single evaluation methods, diversification, and finally to a transition from initial great uncertainty to the final trend of the rationality in the evaluation results. Currently, the evaluation outcomes are more closely aligned with the actual geological circumstances. Furthermore, the evaluation results obtained using disparate evaluation techniques exhibit a high degree of concordance. It is reasonable to conclude that the global marine gas hydrate resource volume of n×10^{15} m^3 is a plausible estimation magnitude.

5.2. Resource evaluation phase

Since the middle and late 1990s, with the collection of abundant global gas hydrate exploration data, increasing research degree, and continuous improvement of resource evaluation technology, the basic theory, research ideas, and evaluation process of resource evaluation have matured considerably compared with the first two stages. Additionally, the value of the evaluation parameters and the rationality of the evaluation results have also been assessed. The evaluation methods of NGHs resources have undergone significant development and have achieved greater accuracy. The parameter settings of the volumetric method, genetic method, and analog method are more closely aligned with the actual geological conditions, and the results of the various evaluation methods are highly consistent. The United States, Japan, and Republic of Korea have all conducted national assessments of the gas hydrate resource potential. By integrating previous data and digital simulations, Boswell et al. concluded that the total amount of methane in marine gas hydrates is approximately 2.83×10^{15} m^3. This is generally consistent with the lower bound of the 2009 DOE 105-106TCF estimate (Boswell R and Collett TS, 2011).

5.2.1. United States

The 1995 National Oil and Gas Assessment was conducted by the United States Geological Survey (USGS) to evaluate the potential for undiscovered conventional and unconventional oil and gas resources in the United States. This evaluation included the first systematic evaluation of in situ gas hydrate resources in both terrestrial and marine areas of the United States (Collett TS, 1995). A total of 11 gas hydrate zones were identified in four marine and one terrestrial region. The majority of the marine gas hydrate mineralization areas are located in the Alaska Sea, the Pacific Ocean, the Gulf of Mexico, and the Atlantic Ocean. The only land metallogenic area is located in the North Slope in Alaska. The USGS considered several factors in its evaluation of the gas hydrate resources in the United States, including the content of biogas, thickness of the biogas source layer, thermogenic gas supply, time, probability of effective migration, reservoir rock facies, trapping mechanism, effective porosity, hydrocarbon accumulation index, range of the hydrate stability zone, reservoir thickness, hydrate saturation, and hydrate gas content. Based on the above limited actual parameters, a preliminary evaluation of the gas hydrate resource zones in the ocean and land in the United States was conducted, and the approximate probability distribution of the gas hydrate resources in each zone and the entire United States was calculated. The calculated gas hydrate resources were almost equal to the total amount of methane in the gas hydrates (Collett TS, 1997). The evaluation consisted of two parts: (1) Risk assessment of the zone attributes to assess the probability of the existence of gas hydrates in the zone. (2) the parameters of the hydrate content were evaluated to determine the probability distribution of the possible hydrate content in the zone. In general, the probability values of each parameter were determined based on the seismic, geological, and geochemical information (water depth map, sediment thickness distribution map, total organic carbon content in the sediments, seabed temperature, geothermal gradient, and hydrate stability temperature and pressure domain distribution map) and data for similar areas. The calculation was divided into three steps: (1) Determination of whether the zone contains hydrates; (2) determination of the number of hydrates in the zone; and (3) combination of the results of the above two steps to consider the statistical resource potential.

The final estimate of methane gas processing in the United States, as determined by the USGS, is 9067×10^{12} m^3. Of this total amount, 52.6% are located in the Alaskan Sea, 19.1% are located in the Pacific Ocean, 12.0% are located in the Gulf of Mexico, 16.1% are located in the Atlantic Ocean, and 0.2% are located in Alaska (Xiao HZ and Zhang Z, 2021). On September 10th, 2019, the USGS released the *Alaska North Slope Undiscovered Gas Hydrate Resource Assessment Report*, which used newly acquired three-dimensional seismic data and a more comprehensive understanding of the characteristics of gas hydrate reservoirs. A more precise estimation of the potential gas hydrate deposits in the tundra in the North Slope in Alaska was conducted. The assessment results indicated that the average technically recoverable resources of the gas hydrate deposits in the region are 1.5 trillion cubic meters of gas.

5.2.2. Japan

The offshore waters of Japan are rich in gas hydrate resources. The Japan Petroleum, Natural Gas and Metal Mineral Resources Agency conducted an investigation that confirmed the existence of gas hydrate resources in the Kurishima Ridge and the Nanhai Ditch of the Okujiri Ridge.The Geological Survey of Japan has calculated the amount of NGHs resources in these areas since 1992. The fundamental concept underlying this calculation and the results of the calculation of the sea area resources are described below.

The fundamental concept is as follows: The original resources (Q) expected for the exploration and development of NGHs fields is theoretically the sum of the total gas (Q_H) generated via the decomposition of NGHs, the total free gas (Q_G), and the total dissolved gas (Q_L) contained in the interlayer water. That is, $Q = Q_H + Q_G + Q_L$.

The quantity of resources (Q_H) of the gas decomposed from the NGHs is determined by multiplying the amount of methane (V) in the NGHs and the accumulation rate (R). The final recoverable resources (G_H) are calculated by multiplying the decomposed gas resources (Q_H) by the recovery rate (B). That is,

$$Q_H = V\times R = A\times\varDelta Z\times R\times\varPhi\times H\times E,$$

$$G_H = Q_H\times B.$$

It is commonly accepted that there is no free gas present in the gas hydrate stability zone as the quantity of free gas (Q_G) is the amount of free gas in the trap below the gas hydrate stability zone. It is therefore more appropriate to calculate the natural gas buried in a conventional gas field.

Currently, the amount of free gas resources under the NGHs layer is calculated using the following formula:

$$Q_G = A_G\times\varDelta Z_G\times R_G\times\varPhi_G\times P/P_0\times T_0/T\times(1-W),$$

$$G_G = Q_G\times B_{G,}$$

where Q_G is the initial free gas resources; G_G is the ultimate recoverable free gas resources; A_G is the free gas distribution area; $\varDelta Z_G$ is the mean thickness of the free gas layer; R_G is the concentration rate of the free gas; Φ_G is the mean porosity of the sediments; P is the formation pressure; P_0 is the standard state pressure; T is the absolute temperature of the sediments; T_0 is the absolute temperature in the standard state; W is the water saturation rate of the sediments; and B_G is the free gas recovery rate. ($A_G \times \Delta Z_G \times R_G$) is the volume of the free gas deposits under the gas hydrate layer.

Because dissolved methane is always saturated in the pore fluid of the hydrate and free gas layers, the amount of dissolved gas (Q_L) contained in the pore water of the hydrate and free gas layers can be calculated using the following formula:

$$Q_L = V \times R = A \times (\Delta Z_H + \Delta Z_G) \times \Phi \times (1-H) \times S \times R,$$

where A is the distribution area of NGHs; ΔZ_H and ΔZ_G are the thickness of the hydrate reservoir and free gas layer below the hydrate layer, respectively; Φ is the porosity of the reservoir sediments; H is the saturation of the gas hydrates in the reservoir sediments; and S is the saturation concentration of the dissolved gas in the reservoir pore water. The saturation concentration of the dissolved gas in the pore water in the hydrate and free gas layers is a function of the in situ temperature, pressure, and salinity. It is usually quantitatively calculated using the following common formula (Lu ZQ and Sultan N, 2008):

$$S = \exp(0.061695 \times T - 6.7898800 + 0.0005372 \times P - 0.0001153 \times P^2).$$

The dissolved gas resources are considerably less than the methane resources contained in the gas hydrate reservoir; therefore, it can be disregarded when calculating the number of resources.

According to the aforementioned methods, the amount of NGHs resources in the waters near Japan was estimated to be 10×10^{12} m^3 by the Japan Institute of Industrial Technology (Fujii T et al., 2008).

5.2.3. Other countries

Russia (Soviet Union) was one of the first countries to discover and comprehensively investigate and potential of NGHs resources. In 1969, the Mesoyaha gas field in Siberia was successfully exploited, demonstrating the viability of extracting natural gas from hydrates. Russian scholars have estimated that the total volume of NGHs resources in the sea and land areas in Russia is approximately 800–1100 $\times 10^{12}$ m^3. The NGHs resources in the sea area range from 200 $\times 10^{12}$ to 7.7 $\times 10^{18}$ m^3, while those in the land range from 31 $\times 10^{12}$ to 350 $\times 10^{15}$ m^3.

The majority of the NGHs resources in Canada are distributed in the Arctic permafrost and numerous continental shelves. The NGHs reserves in these areas have been conservatively estimated to be (0.01–1) $\times 10^{12}$ m^3, and the potential methane reserve has been estimated to be (1–100) $\times 10^{12}$ m^3.

In 1996, India initiated and executed the Indian National Gas Hydrate Plan through the Natural Gas Company Limited, which revealed the existence of a considerable amount of NGHs resources in the continental margin of India. The volume method was used to predict the resource reserves in India's exclusive economic zone, and the result was 1894 $\times 10^{12}$ m^3.

In 2005, Republic of Korea launched the Korea Gas Hydrate 10-year Plan with the support of the Ministry of Knowledge Economy. This plan involved conducting geophysical and geological surveys in the Ulyong Basin in the East Sea of Korea, which yielded a substantial quantity of 2-D and 3-D seismic data, gas hydrate samples, and sediment samples. Based on the seismic data and logging data for UBGH1, the NGHs resources in the central region of this basin were evaluated. The results indicated that the average in situ gas hydrate resources in the surveyed area are 1.7 trillion cubic meters and that the average in situ gas hydrate resources in the sandy reservoir are 0.88 trillion cubic meters.

6. Prediction of gas hydrate resource potential in the South China Sea

In the 1990s, China began its preliminary research and prediction of the NGHs in the South China Sea and the Tibetan Plateau. In 2002, China started to systematically evaluate the NGHs in the South China Sea, East China Sea, and tundra zones (Huang YY et al., 2008). Subsequently, NGHs samples were successively obtained in the Ledong-Lingshui-Songnan zone in the southern part of the Qiongdongnan Basin, the Shenhu area in the Baiyun Sag in the central-southern Zhujiangkou Basin, the eastern part of the Zhujiangkou Basin, and the southwestern slope of the Nanhai Terrace (Su PB et al., 2017a, 2017b, 2021; 2020; Yang SX et al., 2017; Zhang GX et al., 2017). NGHs have been identified using geophysical, geochemical, and submarine cold seep markers in the Xisha Trough, Nansha Trough, Brunei-Shaba Basin, and Wan'an Basin in the China Sea (Chen JW, 2014; Su PB et al., 2010).

Thirty-six evaluations of the NGHs resources in the South China Sea have been carried out by the China Geological Survey, China National Petroleum Corporation, China National Offshore Oil Corporation, and Chinese Academy of Sciences, and the results indicated that the prospective resources are (42–138) $\times 10^{12}$ m^3, mainly ranging from 630 $\times 10^{12}$ to 882 $\times 10^{12}$ m^3 (Table 2). According to the evaluation results for some key sea areas in the South China Sea, the gas hydrate resources are predicted to be (1.6–5.7) $\times 10^{12}$ m^3 in the Qiongdongnan Basin (Chen DF et al., 2004; Liu J et al., 2019), (1.6–13.8) $\times 10^{12}$ m^3 in the southwest Taiwan Basin (Bi HB et al., 2010), (16–100) $\times 10^{9}$ m^3 in the Shenhu area (Wang XJ et al., 2014a; Wang XJ et al., 2014b; Wu NY et al., 2010), (100–150) $\times 10^{9}$ m^3 in the Dongsha area (Sha ZB et al., 2015), and 24 $\times 10^{12}$ m^3 in the Okinawa Trough in the East China Sea (Chen JW, 2014). Compared with the sea area, there is a great difference in the estimation for land permafrost areas, and the total amount of NGHs resources in China is predicted to be (3–75) $\times 10^{12}$ m^3 (Wang X et al., 2018; Zhu YH et al., 2010).

Table 2. Summary of evaluation methods and results of gas hydrate resources in the South China Sea.

Method	Result/ 10^{12} m^3	Reference
Volumetric method	74.4	Su PB et al., 2022
	69.2	Huang YY and Zhang GX, 2009
	64.968	Liang JQ et al. (2006); Zeng FC et al., 2006
	84.5	Zhang GX et al., 2002
	67	Yao BC, 2001
	138	Trung NN, 2012
	63	Ge Q et al., 2006
	88.2	Zheng M et al., 2019; Zou CN et al., 2019
	69.3	Zhu QG, 2004
Genesis method	166	Huang YY and Zhang GX, 2009
	42	Wang JL et al., 2018
Comprehensive method	80	Liang JQ, 2017); Wang SL and Sun ZT, 2018
	67	Yao BC et al., 2008
	64	Yang MZ and Zhang GX, 2007
	69.3	Yu XH et al., 2019
	68	Gao DT, 2017
	70	Chen HN et al., 2010; Hu WR et al., 2010; Zong XX et al., 2017
	70.785	Fu Q et al., 2015
	64.97	Wang N et al., 2015; Wang ZM et al., 2010; Wei W et al., 2009; Zhang JH et al., 2009
	64.968	Sun LD et al., 2013
	74	Gong XF et al., 2014
	65	Chen JD and Meng H, 2013; Ning N et al., 2009; Zhang HS, 2014

The investigation and evaluation of NGHs resources is a long-term basic research work. Since 1999, the China Geological Survey has completed a general survey of the northern South China Sea, and has completed a census of favorable areas in key areas such as Shenhu, Qiongdongdong, and Dongsha, as well as detailed investigation in some of the key mineralized areas. Three types of NGHs deposits, namely, diffusion type, seepage type, and composite type, have been discovered; a theoretical understanding of the systematic and dynamic formation of NGHs has been gained (Fan SS et al., 2007); and a graded evaluation system for the NGHs resources in the South China Sea has been established. The evaluation of the predicted resources in the prospect area has been completed; furthermore, the inferred resources in the favorable zones in the northern South China Sea and the control resources in the mineralized zones have been estimated. The volumetric method based on the Monte Carlo algorithm was adopted for the study of the prospective areas and favorable areas with a low degree of investigation, while the volumetric method based on a geological model and the genesis method based on a basin simulation were adopted for the mineralized areas with a high degree of investigation. Based on the current degree of investigation and the types of special NGHs deposits, the NGHs resource zoning and grading evaluation system was established according to the theory of NGHs system genesis, in which the volume method based on the Monte Carlo algorithm was used for resource evaluation in the prospective area. The parameters are mainly based on the following: geological geophysical, geochemical, and drilling survey data, the distribution area of the prospective area was obtained. According to the spatial distribution characteristics of the sedimentary basins and the types of NGHs deposits, based on the spatial distribution characteristics of the sedimentary basins and the types of NGHs deposits, for the northern South China Sea, based on the actual survey data, including 2-D and 3-D seismic, drilling logging, coring, and other practical exploration data, the probability distribution characteristics of the calculated parameters of the NGHs reservoirs, such as the thickness, porosity, and saturation, were obtained using the partition for the southern South China Sea. Additionally, typical areas, such as Shenhu, Qiongdongdong, and Dongsha areas, were used as scale areas to obtain resource evaluation parameters under similar geological background conditions through analogy.

As the current investigation degree is still limited, most of the areas can only reach the level of predicted resources, and local key areas such as the Shenhu Sea production test area, Qiongdongnan basin production test area, and Dongsha drilling area are close to the level of controlled resources. The predicted resources in the South China Sea gas hydrate prospect area obtained using the volumetric method based on the Monte Carlo algorithm are approximately 37.6×10^{12} m^3 with a 90% probability, 69.6×10^{12} m^3 with a 50% probability, and 117.7×10^{12} m^3 with a 10% probability, with a mean value of approximately 74.4×10^{12} m^3. The ore body-controlled resources in the gas hydrate mineralization zone in the Shenhu area obtained using the volumetric method and based on a three-dimensional geological model are approximately 100×10^9 m^3, and the number of resources obtained using the genesis method based on a basin simulation is 210×10^9 m^3.

7. Discussion

The evaluation of the NGHs resource potential has been an active research topic in scientific and industrial circles. As the understanding of the physical and chemical properties of NGHs, the endowment environment, and the conditions of the formation of hydrate reservoirs have deepened, the accuracy of predictions of NGHs resources has increased. However, there are still three aspects that are worth discussing.

7.1. Resource classification system

There is no uniform classification system for NGHs resources in the world. The classification system for the NGHs resources in the South China Sea is based on a comprehensive understanding of the geological characteristics and economic conditions of NGHs and is an important basis for the evaluation of marine NGHs resources. First, in the general investigation stage, the prospective area is defined, and the resources are evaluated and predicted. The evaluation method of assuming the distribution of the NGHs in the stability zone in the entire evaluation sea area in the early evaluation stage in the international arena is inappropriate, as it does not consider the basic material conditions for the formation of NGHs. Moreover, the prospective area circled in the general investigation stage should consider the gas source conditions, transportation conditions, and distribution range of the reservoir when investigating the formation of NGHs. The second step is to circle the favorable area in the census stage and to evaluate and deduce the amount of resources. The circled favorable area should have the geophysical, geological, and geochemical anomalies related to the NGHs distribution characteristics and scope. Third, the mineralization area should be circled in the detailed investigation stage, and the number of resources should be evaluated and controlled. In this stage, drilling wells are constructed for verification, and the hydrate reservoirs are confirmed through logging and coring. In the circled mineralized areas, the initially identified types of NGHs deposits, the characteristics of the ore bodies, and the production status of the ore bodies should be known. Fourth, blocks are implemented in the exploration stage to evaluate the resource reserves and to determine the recoverable coefficients of the in-situ resources; however, the hydrates are still in the stage of trial mining, and the conditions for calculating the recoverable reserves are not yet in place at the moment.

7.2. Resource evaluation methods

Currently, NGHs resource evaluation methods mainly include the volumetric, genesis, and analogical methods. The volumetric method takes the state of NGHs as the research object to carry out an evaluation, making it a type of static evaluation method, and it requires a large amount of data from survey. The causative method involves taking the source of the gas hydrates as the research object. It is a dynamic evaluation method, but it requires much basic research support. The analogical method can rapidly evaluate the evaluation area through analogy with typical scale areas. It requires the establishment of different types of hydrate scale areas. In addition, some scholars in China have used the 29 sets of global gas hydrate resource data published by previous authors to conduct trend fitting so as to predict the change trend of gas hydrate resources (Pang XQ et al., 2021). However, the prediction results are not informative due to the small data sample, the low and inconsistent level of the resources, and unrepresentative choices.

In terms of static evaluation, the volumetric method based on the Monte Carlo algorithm, or the Latin hypercube algorithm, is the mainstream uncertainty evaluation method. The scientific estimation of hydrate resources using this method requires the collection of massive field investigation data. This method is mainly based on the measured data from geological, geophysical, geochemical, and drilling surveys and focuses on the comprehensive geological and geophysical response characteristics of the middle and shallow subsurface. Furthermore, this method carries out a hierarchical evaluation of prospective, favorable, and mineralized areas so as to effectively avoid the exploration risks caused by a single value of the area coefficient, the aggregation coefficient, and the enrichment coefficient. According to the spatial distribution characteristics of sedimentary basins and the types of gas hydrate deposits, based on high-resolution seismic interpretation, logging analysis, and experimental testing, we can constrain the distribution of the spatial parameters using the thickness, porosity, saturation, and gas production factor calculated from actual exploration data. Additionally, we can construct a geological model using the gridded method and evaluate the non-homogeneity based on consideration of the distribution characteristics of hydrates to avoid mean value prediction and probabilistic statistics to the maximum extent. Thus, the evaluation errors caused by mean value prediction and probability statistics are avoided.

In dynamic evaluation, the genesis method based on the conservation of matter considers the overall process of gas hydrate formation from source to sink. The NGHs formation process has stage continuity. The study of hydrocarbon generation and discharge history involves integrated evaluation of the regional deep and shallow organic matter sedimentary evolution, thermal history, and multi-source hydrocarbon generation process based on the results of deep oil and gas exploration. This method considers the international mainstream biogas genesis system and also includes conventional oil and gas resources. Transport process analysis integrates multidisciplinary data about the deposition, tectonics, and fluids in the middle and shallow parts of the region and focuses on the precise identification and quantitative characterization of the parameters of the fractures, fissures, and high-permeability layers in three dimensions. Furthermore, this analysis considers the influence of the uneven spatial distribution of the gas source on the discontinuous distribution of the hydrate resources. Simulation of the aggregation and formation dynamics relies on the developed hydrate biogenic gas and thermogenic gas production model. Based on the paleo-topographic reconstruction, reservoir parameter prediction, and hydrate formation dynamics parameter experiments, the hydrate saturation parameter prediction in the phase equilibrium stability domain, combined with regional prediction parameters, can effectively improve the credibility of the resource evaluation results.

In terms of comparability analysis, it is essential to define specific scale areas for analogical evaluation under varying endowment and geological conditions. NGHs resources are significantly different from conventional oil and gas resources in terms of the source-storage relationship, transportation mode, aggregation mode, and distribution characteristics. For areas with a low exploration level such as the southern South China Sea, analogies of the resource abundance will be made based on the basic geological conditions for reservoir formation. For areas with a high exploration level such as the northern South China Sea, analogies of key parameters for the gas source, transportation, and aggregation for reservoir formation are emphasized. The analogy method should be based on analyzing drilling areas with similar geological backgrounds and evaluating the evaluation parameters and indices as a whole. Simply using a typical sea area or drilling data for a simple parameter analogy or assumption of a series of coefficient analogies will inevitably lead to distortion of the results.

7.3. Resource evaluation results

According to the progress of investigation and evaluation system, the evaluation of hydrate resources in international waters has not yet involved the link of geological reserves, and the evaluation of geological resources has mostly been carried out in water areas.

The results of gas hydrate resource evaluation in international waters indicated that the global marine gas hydrate geological resources are n $\times 10^{15}$ m^3 and that the predicted resources in the South China Sea gas hydrate prospect area are approximately 74.4 $\times 10^{12}$ m^3. The overall resource abundance is approximately 230 $\times 10^6$ m^3/km^2, which is comparable to the evaluation results of the Nankai Trough of Japan (approximately 160 $\times 10^6$ m^3/km^2), the Gulf of Mexico of the United States (approximately 260 $\times 10^6$ m^3/km^2), and the Ulleung Basin of Republic of Korea (approximately 180 $\times 10^6$ m^3/km^2). It is also comparable to that of the South China Sea NGHs resource abundance estimated by PetroChina, CNOOC, Chinese Academy of Sciences, and the China University of Geosciences (170–240 $\times$ 10^6 m^3/km^2). The results of the evaluation are within a reasonable range.

It should be noted that despite the great prospects for the NGHs resources in the South China Sea, technical and environmental challenges should be overcome to reach economic exploitation (Lu C et al., 2023). Therefore, future research and development efforts should focus on further improving the accuracy of resource evaluation, developing effective exploitation technologies, and ensuring environmental safety and economic viability in the exploitation process

8. Conclusions

(i) This study developed a large-scale, hierarchical, multidisciplinary resource evaluation system framework based on the understanding of the formation of NGHs systems. A hierarchical evaluation system for the NGHs resources was established, and evaluation of the predicted NGHs resources in the South China Sea was conducted based on data from many years of exploration using different evaluation methods.

(ii) Compared with the evaluation results for NGHs resources in typical seas around the world, the predicted abundance of the NGHs resources in the South China Sea is comparable to that in the Gulf of Mexico and is better than those in the Nankai Trough and the Ulleung Basin, with a total amount of n $\times 10^{13}$ m^3. In addition, the distribution of these resources is relatively centralized, which is potentially valuable for exploitation.

(iii) The reasonable valuation range of global NGHs resources is n $\times 10^{15}$ m^3, which is larger than the known natural gas reserves. However, effective economic exploitation still faces many challenges, and countries need to intensify their efforts in exploration and exploitation research to contribute to the realization of the global dual-carbon goal.

CRediT authorship contribution statement

Pi-bo Su, Wei Wei and Jin-qiang Liang conceived of the presented idea. Pi-bo Su, Yun-bao Sun and Yao-yao Lü carried out the original manuscript. Huai Chen, Wei-feng Han and Wei Zhang carried out the editing. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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