



Article Potential and Distribution of Natural Gas Hydrate Resources in the South China Sea

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Abstract: The amount of natural gas contained in the world's gas hydrate accumulations is enormous, but these estimates remain highly speculative. So far, it is still challenging to locate spatial distribution of marine gas hydrate and quantitatively characterize the evaluation parameters and systematic improvement of evaluation systems. Considering the systematic review of the key accumulation factors, such as heat flow, deposition rate and total organic carbon in the typical passive continental margin, the evaluation results of global marine gas hydrate resources were analyzed based on the characteristics of gas hydrate geology, geophysics and geochemistry anomalies in the South China Sea. We analyze the problems on the evaluation of marine gas hydrate resources, probing into the geological characteristics and distribution laws of marine gas hydrate resources in the South China Sea, and estimate the parameters for in-place resource evaluation, in which the volume method based on Monte Carlo probability was used to evaluate the gas hydrate potential resources in the South China Sea. The probability distribution ranges from 37.6 billion (with 90% probability) to 117.7 billion (with 10% probability) tons of oil equivalent, with an expected value of 74.4 billion tons of oil equivalent. The study results show that the gas hydrate resource density in the South China Sea is similar to that in the typical sea areas, and the estimated global resources are basically consistent with the assessment results at this stag; this shows that the South China Sea has great potential for gas hydrate resources. The research results can provide guidance for the evaluation of global climate change and the exploration and development of hydrate resources.

Keywords: natural gas hydrate; resource evaluation method; resource prospect; resource quantity; South China Sea

1. Introduction

Gas hydrates are naturally occurring icelike combinations of natural gas and water that have the potential to provide an immense resource of natural gas from the world's oceans and polar regions. The volume of natural gas contained in the world's gas hydrate accumulations is generally accepted to greatly exceed that of known gas reserves [1]. The presence of gas hydrates is controlled by several factors, among which, low temperature, high pressure, gas composition and abundance, free water and storage space are key parameters. Gas hydrates in marine environments are found in the Pacific Rim between 500 and 2100 m deep, on both sides of the Atlantic, in the northern Indian Ocean, in the Antarctic and in the Arctic; inland seas such as the Mediterranean, Black Sea and Caspian



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Sea are also scattered. To date, more than 240 gas hydrate sites have been found, either directly or indirectly, and about 97% of them are in the ocean (Figure 1).

Figure 1. The map of global gas hydrate distribution (after Bogoyavlensky et al., 2018 [2]); 1—hydrate confirmed by drilling cores; 2—hydrate predicted by logging analysis; 3—hydrate indirectly inferred from seismic data; 4—hydrate published resource evaluation results.

As a kind of back-up, high-efficiency and clean energy, the potential resource of gas hydrate has attracted great attention around the world, especially in developed countries and energy-deficient countries. Since the 1980s, the US, Japan, India, Canada and South Korea have developed national plans for gas hydrate research, development and utilization, and invested heavily in gas hydrate research and evaluation. Studies have shown that marine gas hydrate deposits have been found in thickness from a few centimeters to tens of meters, with continuous distributions of thousands of square kilometers; in some marine gas hydrates, the gas content can be as high as one trillion to one hundred trillion cubic meters [3]. For example, the area south of the Black Plateau on the eastern edge of the US mainland has hydrate resources of about 35 billion tons of oil equivalent, while the Canadian mainland of Vancouver Island has gas hydrate resources of about 100 billion of oil equivalent. The gas hydrate off the coast of Cape Omaezaki, Shizuoka Prefecture contains a gas hydrate of about 74 billion tons of oil equivalent. Marine gas hydrate resources are on a scale unmatched by other conventional gas resources. The industrialization of gas hydrate has great strategic significance for controls of carbon dioxide emissions and carbon neutrality. Prior to its industrialization, an economic evaluation of production capacity for each well should be conducted to determine whether it is profitable at various gas prices. A new hybrid method based on the discounted cash flow (DCF) method and the energy return on investment (EROI) method is used to estimate the economic production rate of gas hydrate exploitation at four different gas price scenarios. The results show that the lowest production rate to make NGH exploitation economic ranges from 1.96 to $29.60 \times 10^4 \text{ m}^3/\text{d/well}$ [4].

The South China Sea is recognized as a potential gas hydrate resource area. The Cenozoic sedimentary basins in the continental margin of the South China Sea, are good candidates for gas hydrate in terms of good gas source conditions and suitable temperature and pressure environments, which are favorable geological basis for the formation and accumulation of gas hydrates. Over the past two decades, the estimated value of prospective resources/in situ gas content of gas hydrate systems in the South China Sea have been in the range from 6 trillion cubic meters (TCM) to approximately 87 TCM. The prospective resource data have certain guiding significance for carbon cycle research and energy strategic planning. However, because the prospective resource quantity is inferred based on limited data and the calculation method is simple, it can be used to describe the

overall distribution of regional hydrate, but the state of hydrate accumulation is not taken into account. The result is uncertain that it is not an accurate gas hydrate resources value and can only be used to judge whether it is likely to be a resource or not.

The difference in the evaluation results of prospective natural gas hydrate resources in the South China Sea reflects the complexity and uncertainty of geological conditions related to natural gas hydrate formation. Although China has implemented six hydrate drilling campaigns and two rounds of trial mining in the South China Sea, the fundamental geological problems for marine hydrate accumulation are still not completely answered. For example, what are the characteristics of gas hydrate spatial distribution? How can you effectively predict evaluation parameters? What are reasonable evaluation methods for resource prediction? These problems are directly related to the reliability of the evaluation results.

In this paper, based on the data on the key elements of gas hydrate accumulation found worldwide, combined with the published evidences of gas hydrate accumulation in the South China Sea, we will comprehensively sort out the comprehensive abnormal response characteristics of marine gas hydrate, systematically analyze the in-place resource evaluation parameters and scientifically evaluate the potential of gas hydrate resources in the South China Sea. It can be used as a reference for the evaluation of global marine gas hydrate resources.

2. Data and Methods

The China Geological Survey (CGS) conducted six gas hydrate drilling campaigns in the South China Sea, including two drilling campaigns in Shenhu sea area in 2007 and the east of the Pearl River Mouth Basin in 2013 [5]. Meanwhile CGS obtained a large number of seismic logging and real samples, which were not used in the early prospective resource evaluation [5,6]. A large number of integrated anomalous responses of marine gas hydrate has been found [5].

2.1. Seismic Data

Seismic data are essential to delineate the lateral distribution of the marine gas hydrate system and estimating parameters. The BSR, strong amplitude reflection and velocity anomalies interpreted from seismic data can be used to identify natural gas hydrate systems and significantly improve the success rate of hydrate drilling [7]. In this study, the parameters were estimated by typical line survey in hydrate prospect area. Each prospect area has 2 survey lines and the survey line intersection is located in the middle of the prospect area, basically representing the overall characteristics of hydrate distribution in the prospect area.

2.2. Logging Data

The logging data can provide high-resolution, continuous and reliable data for quantifying the vertical distribution of marine gas hydrate and obtaining the physical properties in situ. According to the P-wave velocity, gamma ray and resistivity anomalies, the exploration efficiency can be effectively improved and the drilling risk can be reduced. Six well logging stations representing different types of hydrate were selected, including two stations in Dongsha sea area, Shenhu sea area and Qiongdongnan sea area, which basically represent the overall characteristics of pore-filling, fracture-filling and mixed-filling hydrates.

2.3. Drilling Data

Drilling data are the direct evidences to confirm the existence of marine gas hydrates and analyze the occurrence type of gas hydrates. The drilling results in the South China Sea show that hydrate exists in the fissures and pores of seabed sediments in various forms such as massive, layered, lenticular, nodule, vein and disseminated. The lithology is mainly clay, silty clay, fine-grained sandstone and coarse sandstone. According to the existing cores, natural gas hydrate is mainly divided into pore-filling and fracture-filling types. In Shenhu area, the hydrate is mainly distributed in silty sediments and biological shells in the form of pore-filling, while in the Qiongdongnan and Dongsha area it is mainly distributed in argillaceous silty sediments with tiny particle pores and the hydrate exists in the form of fracture-filling.

3. Key Factors

Gas hydrate formation needs to meet sufficient gas source conditions, good migration conditions, appropriate formation conditions and accumulation processes. Because the dynamic evaluation model has the regional limitation, and the dynamic evaluation parameter is difficult to obtain, the existing evaluation method mostly adopts the static evaluation method; that is, based on the analysis of the distribution characteristics of marine gas hydrate systems, the sediments and fluid properties are quantified and the hydrate accumulation characteristics are combined to describe the hydrate resource that has already formed, and the probability range of total gas content is estimated by evaluating area (volume) and other parameters.

3.1. Distribution Characteristics

A prerequisite for evaluating marine gas hydrate resources is the determination of the spatial distribution of gas hydrate-bearing sediments. The conditions for judging the existence of marine gas hydrate in the South China Sea mainly include: (1) a particulate organic carbon content of at least 0.5% [7] to ensure sufficient gas supply; (2) the existence of coarse-grained sediments, faults, Diapir and other significant geological phenomena in order to locate the active conducting system; (3) great water depth and suitable deposition rate to ensure better temperature and pressure conditions; (4) BSR, amplitude anomaly and velocity anomaly were found. The distribution characteristics affect the spatial distribution of the gas hydrate, the area and thickness.

Based on the exploration practice and knowledge of the China Geological Survey for more than 20 years, in the light of the evidences of multi-scale and multi-disciplines, such as geophysics, geochemistry, geology and biology, gas hydrate in the deep-shallow-surface layers of the continental slope in the South China Sea is predicted. The gas hydrate area of 360,000 square kilometers in the South China Sea is estimated (Figure 2).

In order to obtain a more reliable thickness in the gas hydrate area of the South China Sea, the hydrate stability zone thickness is calculated preliminarily based on depth, temperature and salinity of the South China Sea seawater; combined with well logging interpretation, BSR interpretation, seismic attribute analysis and seismic inversion, it is predicted that the thickness of the gas hydrate system in the South China Sea will not exceed 300 m. The overall distribution is normally distributed (Figure 3).

3.2. Reservoir Properties

Gas hydrates usually occur as pore-filling in relatively coarse sediments (e.g., sandy and silty) or in the form of fracture-filling in fine sediments (clay-rich clays; vein, fissure or nodular). The reservoir properties affect the occurrence form of gas hydrate, while the fluid properties are correlated with the genetic types, which directly affect the porosity and saturation parameters.

3.2.1. Porosity

Porosity is a characterization of the effective reservoir space of gas hydrate. Due to a lack of data related to the morphology and density of actual hydrate-filled fractures, the study only considered the total porosity of sediments, but the secondary porosity is not included. It is assumed that the hydrates in the sediments are only present in pore spaces mainly, which is virtually impossible.



Figure 2. The resource quality of gas hydrate in the South China Sea.



Figure 3. Probability distribution of thickness of gas hydrate system in prospect area.

According to the log evaluation of the gas hydrate drilling area in the northern South China Sea, the porosity of coarse-grained sediments ranges from 0.25 to 0.55, while that of fine-grained sediments ranges from 0.2 to 0.9. A similar range of porosity values has been observed at several stations in the Gulf of Mexico [8,9]. The pore-filled hydrate's porosity range of the Shenhu sea area is 0.3–0.5, while the porosity range of the Qiongdongnan sea area represented by fissure-filled hydrate is 0.2–1 (exposed seabed). Furthermore, there is no apparent relationship between the thickness of GHSZ and the depth/thickness of gas

hydrate occurrence. Since our purpose is to evaluate the resource potential of the whole South China Sea, and we pay more attention to the overall distribution characteristics of regional hydrate resources, all porosity data are counted as a data set. However, the weight of porosity data in different prospects is considered when creating the data set. According to the analysis, the porosity of the gas hydrate system in the South China Sea is normally distributed with an average value of 0.5, and the data are concentrated between 0.3 and 0.7 (Figure 4).



Figure 4. Porosity probability distribution of gas hydrate system in the prospect area.

3.2.2. Saturation

Saturation is the ratio of the volume of gas hydrate to the pore space in sediments. The saturation of gas hydrates can vary greatly depending on the solids that fill the pores in the sand or the solids that fill the cracks in the clay. However, the lithology of natural gas in the South China Sea is relatively simple and mainly siltstone, so the saturation of different lithologies is not classified.

According to the interpretations of wireline logs, LWD logs and cores in the South China Sea, the saturation of gas hydrate in clay-rich fine-grained sediments is relatively low, about 1–10%, but when the sediments contain foraminifers, such as in the Shenhu sea, the saturation can reach 10–40% and at the highest, 48% [10]. According to Cook et al.'s resistivity model, the saturation of gas hydrate in near-vertical fractures in clay is about 3% to 96% [11], and the gas hydrate saturation in clay fractures in the Dongsha and Qiongdongnan areas is relatively high (45% to 100%).

According to the statistical data of hydrate saturation evaluated by well logging at the Shenhu drilling station (Figure 5), hydrate saturation also presents a skewed distribution, with a maximum value of 0.3618 and an average value of about 0.0853. Lognormal, Beta and other theoretical distributions were used to fit the data. The results show that Beta distribution (A = 1.48, b = 15.8614) agrees with the overall distribution characteristics of gas hydrate saturation in the Shenhu area.

Based on the statistical data of hydrate saturation evaluated by logging at drilling stations in the Dongsha area (Figure 6), the saturation presents a very obvious skewness distribution in general, with a maximum value of 0.8879 and an average value of 0.1272. Lognormal distribution, Beta and generalized extreme value (GEV) distributions were used to fit the parameters, and the results showed that Beta distribution (A = 0.4251, b = 2.9179) was more consistent with the overall distribution characteristics of hydrate saturation in the Dongsha area.



Figure 5. Distribution characteristics of hydrate saturation from logging interpretation in the Shenhu sea area.



Figure 6. Distribution characteristics of hydrate saturation from logging interpretation in Dongsha Sea area.

3.3. Enrichment Characteristics

The hydrate volume conversion factor is the gas volume per cubic meter of hydrate at standard pressure and temperature (STP), representing the energy density. This value is related to the cage occupancy of the hydrate lattice, ranging from 140 to 185 [12–16], with an average of 164 (Figure 6). The structural characteristics of hydrate in the Dongsha area in the northern South China Sea are not much different from those in the Black Sea Platform, which proves that the theoretical calculation of the most likely gas-producing factor of hydrate in nature ranges from 121.5 (satisfying 70% gas filling rate) to 160.5 (hydrate index 6.2). Therefore, the aggregation coefficient (also known as the gas production factor) takes a constant of 150 when calculating the number of resources.

4. Evaluation Results

4.1. Evaluation Method

Although natural gas hydrate fills in the in situ formation in solid form, which is quite different from conventional natural gas in the reservoir, the volumetric method is still suitable for the calculation of natural gas hydrate resources, which is also the most widely used method in the world. On the one hand, the volume method can reflect the actual occurrence state, which is convenient to guide the actual development site selection; on the other hand, no matter the volumetric method, the analogical method or the genetic method, they all need to end up in the evaluation of parameters *A*, *Z*, φ , *S*, *E*, so the essence of all evaluation methods is still the one used by the volumetric method.

The basic principle of the volume method is to calculate the number of resources according to the size of the volume. Based on the static occurrence characteristics of natural gas hydrate, the linear relationship between the resource amount and reservoir parameters is established to calculate the resource amount. The mathematical formula can be summarized as follows:

$$Q_h = A_h \times Z_h \times \varphi \times S_h \times E$$

where Q_h is the resource amount of natural gas hydrate (m³); A_h is the effective area (m²); Z_h is effective thickness (m); φ is porosity; S_h is hydrate saturation; E is the gas production factor.

The accuracy of gas hydrate resource evaluation mainly depends on the means, accuracy and reliability of obtaining the five parameters above. According to the means of obtaining parameters in the actual exploration process, there are three methods for selecting parameters of gas hydrate resource evaluation: similar analogy method, indirect measurement method and direct measurement method. Different parameter selection methods are suitable for different levels of exploration stages, and different precision resource evaluation results can be obtained.

It is worth mentioning that the volumetric method is applicable in principle to all stages of gas hydrate exploration, the Monte Carlo-based volumetric assessment is the most scientifically sound in the early prospect assessment stage and for the later stage of ore body evaluation, the result of the volume method based on geological modeling is the most accurate. It is worth noting that for the evaluation of the resources of large-area, evenly distributed pore-filled hydrates, the spatial distribution of hydrate in different lithologic sediments can be roughly described, but for fracture-filled hydrates, it is difficult to define key parameters, such as hydrate saturation, because of the strong heterogeneity of the reservoir and the lack of obvious geophysics response from seismic data.

4.2. Evaluation Results

The evaluation of natural gas hydrate resources in the South China Sea can be divided into four levels according to different exploration and development stages: prospect area, metallogenic zone, favorable block and ore body. The evaluation of the prospective area is the basis, which is directly related to the natural gas hydrate resource base and subsequent exploration direction of a region. A statistical method was used to summarize the geological resources of prospective areas. The volume method formula combined with the Monte Carlo method is the most reasonable method to calculate the potential hydrate resources at present. Based on the measured reservoir parameters in the South China Sea and the Monte Carlo method, the gas hydrate resources in the South China Sea are 37.6×10^{12} m³ with 90% probability and 117.7×10^{12} m³ (Figure 7). Because there is a gas hydrate area of 360,000 square kilometers in the South China Sea, the gas hydrate resource density is 0.21 billion cubic meters (BCM)/km².



Figure 7. Probability distribution map of gas hydrate resources in the South China Sea.

Compared with the early evaluation of gas hydrate resources in the South China Sea by other scholars, the evaluation results fall into the range (Table 1). It should be noted that the evaluation parameters of early stages are based on assumptions; the evaluation parameters are estimated from actual survey data in this paper. Compared with the natural gas hydrate resource density of typical marine settings assessed by foreign scholars, it is similar to that of the Nankai Trough in Japan, the Gulf of Mexico in America and the Ulleung Basin in Korea (Table 2).

Table 1. Evaluation results of prospective resources in the South China Sea gas hydrate prospective area over the years.

The Serial Number	Geological Resources (×10 ¹² m ³)	Area (km²)	Reference
1	86.85	$9.3 imes 10^5$	[17]
2	84.5	$5.9 imes 10^5$	[18]
3	52	$6.0 imes10^5$	[19]
4	64.9	$1.3 imes10^5$	[20]
5	63	$1.88 imes 10^5$	[21]
6	141	$11 imes 10^5$	[22]
7	80.3	$7.69 imes10^5$	[23]

Table 2. Gas hydrate resource density previously estimated by foreign researchers.

The Serial Number	Gas Hydrate Resource Density (BCM/km ²)	Sea Location	Reference
1	~0.24	Nankai Trough	[24]
2	~0.29	Gulf of Mexico	[8]
3	~0.23	Ulleung Basin	[25]

It should be noted that the assessment of gas hydrate resource potential in the South China Sea does not take into account the differences in complex geological conditions, sedimentary heterogeneity and hydrate accumulation, and the types of gas hydrate deposits are not analyzed in detail, resulting in average values.

However, for the evaluation of regional resource potential, this method is reasonable because it does not need to describe the characteristics of hydrate sediments and only needs to investigate the overall distribution of resources. Further evaluation requires further study of gas hydrate accumulation and reservoir formation theories, as these gas hydrates will directly influence the scientific evaluation of gas hydrate resource potential. Therefore, in the future, it is necessary to carry out research on the formation mechanism, mineralization mechanism and reservoir-forming law of multiple types of clathrate hydrate, according to the unique geological conditions in the South China Sea, so as to depict the process of gas generation-migration-accumulation precisely and improve the clathrate hydrate resource estimation methods.

5. Discussion

5.1. Problems in the Assessment of Natural Gas Hydrate Resources in Typical Marine Settings

A proper assessment of the volume of global gas hydrate resources is particularly important to clarify the position of gas hydrate in global resources and the environment.

At present, the evaluation of global gas hydrate resources by different scholars can be divided into three stages. The abundance of gas hydrate methane in the seafloor is mainly due to the abundance of microbial-derived methane in the seafloor sediments and the wide distribution of the seafloor gas hydrate stable zone. Different researchers have different estimates of the amount of methane in the gas hydrate, which is mainly due to the different degree of geological survey work and data mastery in different gas hydrate zones in different sea areas and the different evaluation methods, especially the different parameters adopted by the researchers. With the deepening of exploration, the definition and mastery of the nature of gas hydrate physical chemistry are gradually becoming real, and the selection of the evaluation methods and parameters of gas hydrate resources are more in line with the scientific basis. The findings of the global gas hydrate assessment are beginning to gain early recognition in academia and industry. Although estimates of global gas hydrate resources have declined over the past decade or so compared with previous estimates, the combined projections suggest that the amount of gas hydrate resources exceeds the total amount trapped in existing recoverable gas reservoirs, so it is indisputable that the potential resources of gas hydrate as a new energy source are huge (Table 3).

For example, in the early stages (1970s and 1980s), the gas hydrate was not substantially investigated, and it was generally assumed that the gas hydrates are continuously distributed within a stable zone in the sediment and then, the volume method was used to estimate the global gas hydrate resources. In this stage, because there was no actual survey data, there was a large subjective randomness in the selection of parameters, the results of resource prediction were generally overestimated and the results had great uncertainty.

With the development of the Deep Sea Drilling Program (DSDP) and ocean gas hydrate (ODP) in the 1980s and mid-1990s, people had a clearer understanding of the distribution of ocean waters. Especially for hydrate drilling, the hydrates of the key evaluation parameters provide a direct data base. In this stage, the volume method based on actual data is more reasonable, the evaluation result is basically stable at 10¹⁶ m³ and the difference in evaluation result is obviously reduced.

Since the mid-late 1990s, with the development of global gas hydrate exploration data, the research level and resource evaluation technology, basic theory, research ideas and evaluation process of resource evaluation have been more mature than the first two stages. The value of evaluation parameters and the rationality of evaluation results are also studied, the evaluation method of gas hydrate resource quantity has been developed greatly and the evaluation precision has been further improved. The parameters of the volumetric method, genetic method and analogy method are more close to the actual geological conditions, and the evaluation results of many evaluation methods are consistent. At this stage, it is generally considered that the formation and accumulation of gas hydrates are discontinuous and that the accumulation of gas hydrates is the result of rock pores being filled with gas hydrate in varying degrees; the gas hydrate cannot be distributed continuously over a large area [26]. Most recent estimates range from 10^{14} m³ to 10^{15} m³, due to low estimates of gas hydrate area and gas hydrate saturation. Boswell et al. have calculated that the total

amount of CH₄ trapped in the seafloor gas hydrate is about 2.83×10^{15} m³, consistent with the lowest value estimated by the US Department of Energy. The setting of the parameters of the volumetric method and the analogy method in this stage is relatively closer to the actual geological situation, and the evaluation results of the various evaluation methods are more consistent; the amount of global ocean gas hydrate resources N $\times 10^{15}$ m³ is considered a reasonable estimation.

According to our evaluation results, if the 360,000-square-kilometer sea area contains 74.4 TCM of hydrate gas, then the global ocean area is 360 million square kilometers, the water depth of 2000 m is far lower than that of conventional natural gas, so it cannot be regarded as a prospective area, and the remaining area (about 2.5% of the global total area) is about 2×10^{15} m³ of hydrate gas, roughly in line with current estimates.

$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	Evaluation Phase	Evaluation Method	Ocean (×10 ¹⁵ m ³)	Reference
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		V	3021~3085	[16]
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		V	1135	[27]
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		V	1573	[28]
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	In the early stages	V	1550	[29]
$\begin{array}{c c c c c c c c c c c c c c c c c c c $		V	>0.016	[30]
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		V	110~130	[31]
$\begin{tabular}{ c c c c c c c c c c c } & V & 5~25 & [33] \\ V & 7600 & [34] \\ V & 3.1 & [35] \\ V & 15 & [36] \\ V & 15 & [36] \\ V & 20 & [14] \\ V & 20 & [15] \\ V & 20 & [15] \\ VS & 26.4~139.1 & [12] \\ VS & 22.7~90.7 & [13] \\ VS & 1 & [38] \\ \hline \end{tabular}$		V	3.1	[32]
$\begin{tabular}{ c c c c c c c } & V & 7600 & [34] \\ V & 3.1 & [35] \\ V & 15 & [36] \\ V & 40 & [14] \\ V & 20 & [37] \\ V & 20 & [15] \\ VS & 26.4 \\ VS & 22.7 \\ VS & 1 & [38] \\ \hline \end{tabular}$		V	5~25	[33]
V 3.1 [35] V 15 [36] The discovery stages V 40 [14] V 20 [37] V 20 [15] VS 26.4~139.1 [12] VS 22.7~90.7 [13] VS 1 [38]		V	7600	[34]
$ \begin{array}{c cccc} V & 15 & [36] \\ \hline The discovery stages & V & 40 & [14] \\ V & 20 & [37] \\ V & 20 & [15] \\ VS & 26.4 \\ VS & 22.7 \\ VS & 1 & [38] \end{array} $		V	3.1	[35]
The discovery stages V 40 [14] V 20 [37] V 20 [15] VS 26.4~139.1 [12] VS 22.7~90.7 [13] VS 1 [38]		V	15	[36]
V 20 [37] V 20 [15] VS 26.4~139.1 [12] VS 22.7~90.7 [13] VS 1 [38]	The discovery stages	V	40	[14]
V 20 [15] VS 26.4~139.1 [12] VS 22.7~90.7 [13] VS 1 [38]		V	20	[37]
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VS 22.7~90.7 [13] VS 1 [38]		VS	26.4~139.1	[12]
VS 1 [38]		VS	22.7~90.7	[13]
		VS	1	[38]
V 6.8 [39]	The mature stages	V	6.8	[39]
V 1.5 [40]		V	1.5	[40]
VS >0.2 [26]		VS	>0.2	[26]
VS 3~5 [41]		VS	3~5	[41]
The mature stages VS 1~5 [42]		VS	1~5	[42]
VS 0.28 [43]		VS	0.28	[43]
D 0.0082–2.1 [44]		D	0.0082-2.1	[44]
D ≥0.87 [45]		D	≥ 0.87	[45]
D 2.8 [46]		D	2.8	[46]
D 0.95~5.7 [47]		D	0.95~5.7	[47]

Table 3. Prediction of natural gas hydrate resources in global marine areas.

"V" means volumetric method; "VS" means analogical method; "D" means particle organic carbon deposition rate method.

5.2. Distribution of Natural Gas Hydrate Resources in the South China Sea

Most hydrate deposits have mixed gas sources, and basin margin faults mainly control hydrate-rich areas. The northern part of the South China Sea can be divided into two metallogenic and enrichment zones. The northern enrichment zone is a large sedimentary basin developed in the Cenozoic. The ore-forming gas sources in this enrichment zone are not only shallow biogas, but also part of deep pyrolysis gas. It is divided into three regions from east to west. The eastern region is the north slope of the Taixinan Basin, the middle region is the south slope of the Baiyun Depression in the south margin of the Pearl River Mouth Basin and the western region is the deep-water zone Qiongdongnan Basin. The southern enrichment zone is a paleo-slope region developed in the Cenozoic medium and small sedimentary basins, mainly consisting of hydrates from shallow microbial gas sources. The enrichment zone starts from the Southwest and Bijia Basins in the east, extends

to the Jianfengbei, Shuangfengbei and Shuangfengnan Basins in the west and reaches the Xisha Trough Basin.

(1) Diffuse hydrates with wide distributions, large thicknesses and high saturations are mainly developed in the Shenhu sea area.

It is proved by drilling that diffusive hydrate exists mainly in the Shenhu sea area, found in the Quaternary shallow layer and middle-late Miocene strata. It is in the same area as Baiyun Sag, which is rich in hydrocarbon generation, closely related to the time-space coupling matching of many reservoir-forming factors in different types of gas transmission channels, such as shaly or silty sandstone reservoirs, faults, gas chimneys and so on. The source of gas hydrate gas is mainly methane-based microbial gas with some pyrolysis gas. It is mainly formed by diffusion in porous sediments on the seafloor. The process of gas hydrate formation is relatively slow, but it is widely distributed.

(2) Seepage hydrates with shallow burials, large thicknesses and high saturations are mainly developed in the southeast Qiongdongnan Sea area.

Bulk gas hydrate samples were successfully obtained by gravity column sampling and gas hydrate drilling (Figure 8). A submarine camera survey also confirmed the existence of abundant seepage hydrates in the southeast Qiongdongnan Sea area. Natural gas hydrates occur in cracks/fissures and minor faults in the stable domain of shallow seabed hydrates in the form of massive, layered, nodular, vein-like and other morphological characteristics. The formation and occurrence of NGH are closely related to the general gas migration and leakage caused by sufficient gas supply in the basin. NGH mainly migrates from high-flux methane gas through the tectonic migration channel to the stable region and fills in the fissures, forming a high-saturation NGH orebody. The hydrate tends to generate quickly in the sedimentary layer and has the characteristics of shallow burial, large thickness and high saturation.



Figure 8. Photos of hydrate core samples obtained by drilling in the Qiongdongnan Sea area [48].

(3) The hydrates in the Dongsha Sea area are characterized by multi-stage accumulation, multi-layer distribution, shallow burial, large thickness, multiple types, high ore-bearing rate and high methane purity. It has been confirmed by actual drilling that there are various gas hydrate forms in this area, such as massive, vein-like, nodule and dispersed (Figure 9). Moreover, seepage and diffusion hydrates co-exist in this area, with multi-layer distributions of hydrates, distinctive multi-stage reservoir formation characteristics and unique reservoir formation mechanisms. Hydrate gas is mainly composed of microbial gas, which can develop different types of hydrate in different layers of the same mine through various migration paths, and the content of methane gas in the hydrate is more than 99%.



Figure 9. Gas hydrate samples drilled in Dongsha Sea area [49].

6. Conclusions

(1) There are abundant gas hydrates in the South China Sea. A new Monte Carlo method-based volumetric method is used to estimate the gas hydrate resources of the northern part of the South China Sea. The parameters were calculated using a combination of geological, geophysics and geochemistry data sets, taking into account the probability distributions of variables such as area, thickness, porosity, saturation and aggregation coefficients. It is reasonable to make a static assessment of the gas hydrate resources.

(2) The evaluation results indicate that the gas hydrate potential resources in the South China Sea range from 37.6 billion to 117.7 billion tons of oil equivalent. Since the hydrates found are mainly distributed in silty and sandy sediments, the shaly and sandy hydrate-bearing layers have not been evaluated separately; the evaluation also did not take into account the differences in complex geological conditions, sedimentary heterogeneity and hydrate accumulations, and included predictions for low-exploration areas. Similarly included are the results of high-exploration zones, which also take into account gas hydrate types. Since there is no more suitable method for calculating the amount of leaky hydrate resources, it is suggested that it is advisable to take the average value of the existing methods.

(3) This result shows that the gas hydrate resource density is 0.21 BCM/km² for the South China Sea, which is similar to that of the Nankai Trough in Japan with a density of ~0.24 BCM/km², the Gulf of Mexico with a density of ~0.29 BCM/km² and the Ulleung Basin with a density of ~0.23 BCM/km².

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