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Original Paper

Distribution and resource evaluation of natural gas hydrate in South China sea by combing phase equilibrium mechanism and volumetric method

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ABSTRACT

China Geological Survey conducted the second trial production of natural gas hydrate (NGH) in the Shenhu Area in South China Sea (SCS) from 2019 to 2020. Compared with the first trial production in 2017, the second trial showed significantly increased daily gas production and total gas production, and removed some technical obstacles for large-scale NGH resource developments in the SCS. However, current NGH resource evaluation in the SCS is still at the stage of prospective gas content assessment, which is unable to guide further NGH exploration and development. This study utilized the hydrate phase balance to delineate the NGH distribution range and effective thickness and volumetric method to evaluate NGH resource. Based on the latest exploration and production data from the Shenhu Area, Monte Carlo simulation was performed to calculate the NGH resource amount with different probabilities. By assuming a 50% cumulative probability, the in-situ NGH resources in the SCS was estimated to be 11.7×10^{12} m^3 and the recoverable NGH resources was 2.8×10^{12} m^3. These results will provide a more reliable resource basis for China to formulate comprehensive development strategies for oil and gas exploration in the SCS.

1. Introduction

While shale oil researches were going on (Hu et al., 2021a, 2021b; Wang et al., 2020, 2021a, 2021b), natural gas hydrate (NGH) gradually turned out as an important new energy source with a great resource potential that will replace the conventional oil and gas in the future. Many countries have invested large amounts of money and efforts in NGH drilling and testing (Cui et al., 2018). As of 2019, the world has conducted 19 main voyages of sea NGH drilling, including 6 in the United States, 3 in Japan, 2 in Korea, 2 in India, 1 in New Zealand and 5 in China (Sha et al., 2019). Trial production tests in northern Alaska, northern Canada, northwestern Russia, South Sea Trough Japan, South China Sea and so on have successfully obtained NGH samples (Wang et al., 2017) (Fig. 1), and trial mining technology and research are improving (Cai et al., 2020; Liu et al., 2017; Yang et al., 2017). In the past 20 years, the number of published papers about NGH has dramatically increased from 685 in 2000 to 15,767 in 2020 (data from CNKI). However, it is recognized that the global NGH resource decreased significantly than that estimated by Trofimuk (1973). In detail, the estimate has been reduced to one ten-thousandth of the initial evaluation and the decreasing trend is likely to continue in the future (Pang et al., 2021).

NGH researches and test explorations began relatively late in China, but has made significant achievements. By 2020, Guangzhou Marine Geological Survey has organized 6 hydrate drilling (GMGS 1, 2, 3, 4, 5, 6 voyages) in 2007, 2013, 2015, 2016, 2018 (Liang et al., 2019) and 2019 (Qin et al., 2020), respectively. Two trial

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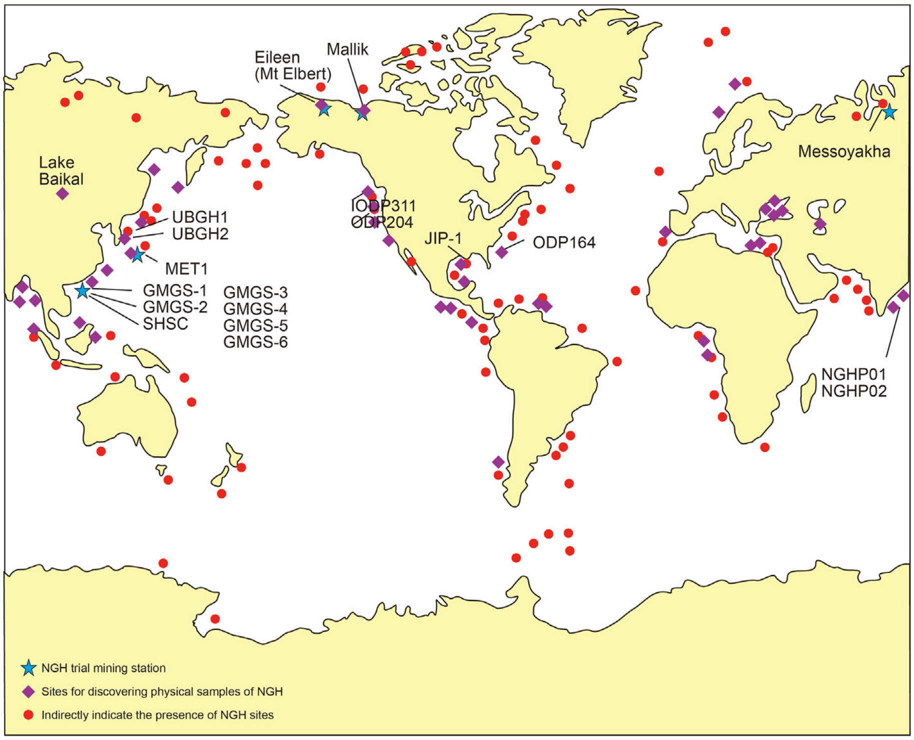

Fig. 1. Distribution of main geological surveys and exploration activities related to natural gas hydrate in the world (modified from Sha et al., 2019).

productions were conducted in 2017 (Wu and Wang, 2018) and 2019 (Ye et al., 2020). 35 NGH resource evaluations were conducted in the SCS in the past two decades, and the estimates ranges from 60×10^{12} m^3 to 90×10^{12} m^3 (Fig. 2), with no obvious changes with time. These estimates are even higher than the global in-situ NGH resources (Boswell, 2009; Boswell and Collett, 2011), which is obviously contrary to the actual situation. Recent studies found that they are only prospective gas resources (Pang et al., 2021). These estimates were mainly calculated by volumetric method, by multiplying parameters of favorable distribution areas obtained from seismic exploration and average porosity, permeability, and NGH saturation from previous studies (Pang et al., 2021). The main problem of the previous estimates is that they do not consider the NGH migration and enrichment and treat all NGH in the gas hydrate stable zone (GHSZ) as resources. Besides, obvious problems exist in parameter determination. On the one hand, some parameters were exaggerated, such as the distribution area and thickness are mainly determined by the GHSZ, whereas drilling results found that the NGH are not formed in the whole GHSZ (Pang et al., 2021). On the other hand, some parameters are underestimated, such as the NGH saturation of reservoirs. Drilling data showed that the NGH saturation in effective reservoirs commonly exceeds 20%, and NGH with saturation below 20% cannot constitute realistic resources. However, the saturation with average of 1.2%–14% was used in previous studies, it may result in pessimistic estimates. In order to obtain more objective parameters, this study investigates basic conditions for NGH formation in the SCS firstly, and delineates the effective NGH area and effective NGH thickness by utilizing phase equilibrium mechanism. Second, according to drilling data of the Shenhu Area in Pearl River Mouth Basin, key parameters such as the area ratio, thickness ratio, porosity, and NGH saturation were obtained. Third, utilizing Monte Carlo simulation and volumetric method to evaluate in-situ NGH resource in the SCS and its distribution probability. Finally, by combing recovery factor obtained from laboratory experiments and Monte Carlo simulation, the recoverable NGH resource and its variation with different probability were obtained.

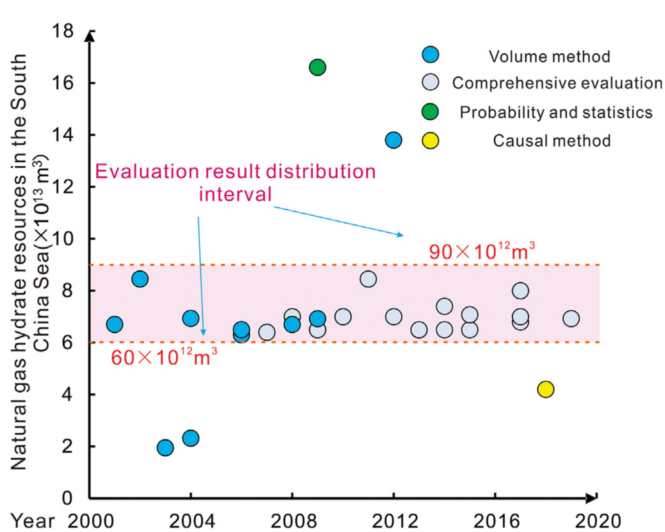

Fig. 2. Assessment results of NGH resources in South China Sea from 2000 to 2020 (modified from Pang et al., 2021).

2. SCS background and NGH distribution

2.1. Basin distribution in the SCS

The SCS covers an area of 3.5×10^6 km^2. Twenty-four sedimentary basins developed in the SCS, with an area 1.06×10^6 km^2 (Feng et al., 2018). Fifteen basins were evaluated in this study, including Taixinan Basin, Pearl River Mouth Basin, Twin Peaks Basin, Qiongdongnan Basin, Yinggehai Basin, Zhongjiannan Basin, Wan'an Basin, Nanwei Basin, Zengmu Basin, Beikang Basin, Nansha Trough Basin, Brunei Sabah Basin, Liyue Basin, Palawan Basin, and Bijia South Basin, with a total area of 7.4 × 10^5 km^2. The Taixi Basin, Taixinan Basin, Pearl River Mouth Basin, Qiongdongnan Basin, Yinggehai Basin, Beibu Gulf Basin, Twin Peaks Basin, Pinnacle Basin and Nanwei Basin located in the northern SCS, the Zengmu Basin, Beikang Basin, Liyue Basin and Wanan Basin located in the southern SCS, and Zhongjiannan Basin and Bijianan Basin located in the eastern and western SCS, respectively. Twelve virtual wells were set up in 12 major basins respectively (Fig. 3).

2.2. Formation conditions and phase equilibrium models of the NGH in basins

All the basins are favorable for the NGH formation. In terms of structure, they are featured with both passive and active continental margins and have developed a variety of geological structures favorable for NGH migration and accumulation, such as submarine landslides, mud diapirs, accretionary wedges, structural slope breaks, and polygonal faults. In terms of sedimentary conditions, the three periods of rapid subsidence in the SCS provided

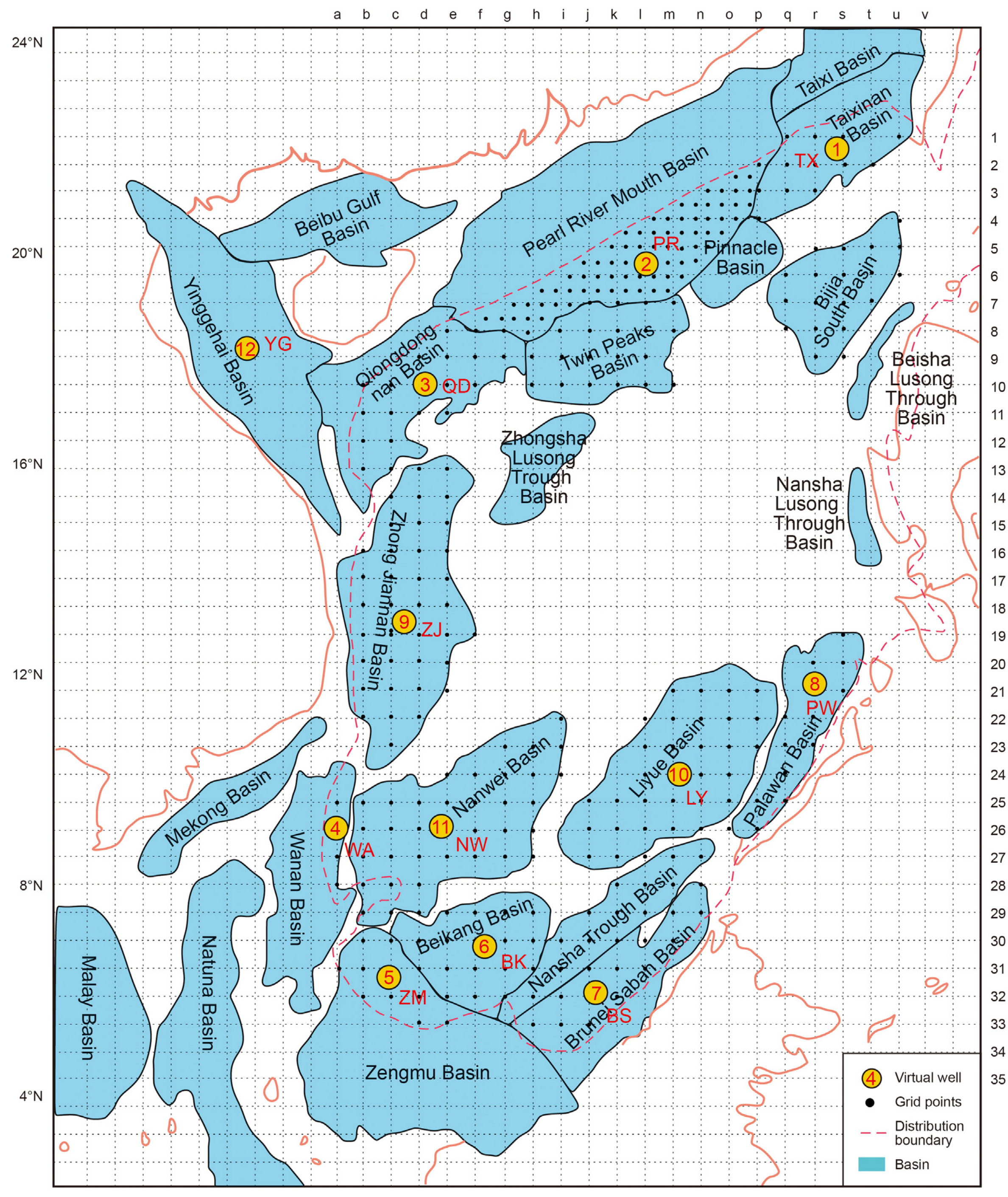

Fig. 3. Overview of the main sedimentary basins and virtual well points in the South China Sea (modified from Feng et al., 2018).

abundant sediments for NGH formation. Besides, the rapid subsidence promoted high sedimentation rates since the Paleogene, which is beneficial for NGH formation in three aspects. First, promoting rapid burial of organic matter so as to avoid oxidation and good preservation; Second, boosting the formation of undercompaction and then forming a well porous reservoir, which is conducive for NGH migration and provides more storage space; Third, reducing the heat flows of the formation and is more conducive to NGH formation. In terms of gas sources, these basins have thick strata and develop multiple sets of source rocks, and lots of conventional oil and gas fields have been discovered, showing good gas source conditions (Luo et al., 2013).

In terms of phase equilibrium conditions, the NGH formation only form in conditions with high pressure and low temperature. The reservoir temperature can be determined by Equation (1) (Zhu, 2007) and (2) (Shi et al., 2015):

$$T = -8.7946\ln Z + 62.958 \quad 100\text{ m} < Z < 800\text{ m} \tag{1}$$

$$T = \exp(6.506617 - 0.7352185\ln Z) \quad 600\text{ m} < Z < 2800\text{ m} \tag{2}$$

where T refers to temperature, °C; Z refers to depth, m.

Liu et al. (2012) analyzed the NGH samples in the Shenhu Area to obtain their mineral composition (Table 1). By inputting the component information of the NGH and temperatures of 283.15 K, 288.15 K, and 293.15 K into the NGH phase equilibrium calculation software CSMHYD, respectively, NGH pressures in three phase equilibrium states were obtained as 6.8 MPa, 11.6 MPa and 21.0 MPa.

According to the NGH phase equilibrium model (Eq. (3)) established by Dzyuba et al. (Zhou et al., 2017), this study sets two coefficients, a and b, to substitute 264.9661 and 9.6339 in the model (Eq. (3)), and then utilize the above three sets of data to calculate and verify the two coefficients so as to obtain a phase equilibrium model for the SCS (Eq. (4)).

$$P = e^{\frac{T-264.9661}{9.6339}} \tag{3}$$

$$P = e^{\frac{T+7.8890}{9.8028}} \tag{4}$$

where T refers to temperature, °C; P refers to pressure, MPa.

Substituting the hydrostatic equation of $P = \rho gh$ into Eq. (4) (where h refers to the sea depth, m; ρ refers to water density, 1.03 g/cm^3; g refers to gravity acceleration, 10 m/s), the NGH phase equilibrium models in the SCS were obtained (Eq. (5)).

Table 1
Gas composition of natural gas hydrate in the Shenhu area of the South China Sea (Liu et al., 2012).

Gas	Hydrate sample gas composition, %		
	HY-1	HY-2	HY-3
C_1	99.66	99.38	99.69
C_2	0.33	0.55	0.3
C_3	0.01	0.07	0.01.
i-C_4	ND	ND	ND
n-C_4	ND	ND	ND
n-C_5	ND	ND	ND
i-C_5	ND	ND	ND
O_2	ND	ND	ND
N_2	ND	ND	ND
CO_2	ND	ND	ND

Note: ND means not detected.

$$H = 227.48e^{0.1075T} \tag{5}$$

Calculated from the Eqs. (1), (2) and (5), the minimum depth for NGH formation in the SCS is 528 m. By combing the water depths of virtual wells from the high-definition map of China (2015) and geothermal gradient data (Bi, 2010; Zhang et al., 2014), key parameters related to the phase equilibrium of NGH were obtained (Table 2).

Based on the key parameters (Table 2), the NGH phase equilibrium models of the 12 virtual wells in the 12 basins were established (Fig. 4). Almost all the basins are conducive to the NGH formation and distribution, except for the Yinggehai Basin, due to shallow sea depth (<528 m) and high seabed temperature (>21.1 °C). The models indicate that the effective thickness for NGH distribution in each virtual wells is greater than 200 m. The effective thicknesses of NGH in the southern Pearl River Mouth Basin, Bijia South Basin, Zhongjiannan Basin, Taixinan Basin, Twin Peaks Basin, and the southern Beikang Basin are up to 450 m, while that of the Yinggehai Basin, Nanwei Basin, Lile Basin, Palawan Basin is much smaller.

2.3. NGH distribution area and thickness prediction

Constraining by the minimum water depth required for the NGH formation in the SCS (528 m), the effective distribution area of the NGH can be delineated. For the effective distribution area, a total of 300 grid points were divided in this study (Fig. 3). Due to the in-depth studies of the Pearl River Mouth Basin, the grid points were refined to make the results more accurate. The water depth and bottom temperature of grid point are obtained from the topographic map of the SCS and Eq. (5). The geothermal gradient in the northern SCS is obtained from the geothermal gradient contour map in the continental margin basin of the northern SCS (Tang et al., 2014), and the average geothermal gradients are used in other basins (Shi et al. 2003, 2020; Gao et al., 2007; Mi et al., 2009; Li et al., 2013; Zhang et al. 2013, 2014). Meanwhile, the geothermal gradients were corrected based on sediment thickness (Huang and Wang, 2006). The correction takes the relationship between actual strata thickness and theoretically calculated thickness into account. For grid wells, when the theoretical thickness is larger than the actual strata thickness, taking the former one as thickness parameter; When theoretical thickness is smaller than the actual strata thickness, taking the latter one as thickness parameter. In this way, the effective strata thicknesses for the NGH development at every grid well are obtained, and the contour map of the NGH thickness was obtained (Fig. 5). Results show that the favorable area for NGH distribution is 550,000 km^2, and the effective average thickness is 282.2 m, showing that abundant NGH resources accumulated in the SCS. In comparison, analyzing form the phase equilibrium mechanism, the Pearl River Mouth Basin, Zhongjiannan Basin, Zengmu Basin, and the Bijianan Basin are relatively richer in NGH resources.

Compared with previous estimates, key parameter determination in this study is much more objective with real drilling data, by constraining the effective NGH thickness with sediment thickness of strata, removing the area with no sediments, and considering the actual phase equilibrium models, and therefore the NGH resource evaluation in this study is more objective and precise.

3. Key parameter determination and resource evaluation

3.1. NGH drilling data in the Shenhu Area

Guangzhou Marine Geological Survey conducted NGH drilling surveys in the Shenhu Area (3000 km^2) in 2007 (GMGS1), 2015

Table 2
Phase equilibrium parameters of virtual wells in 12 main basins in the SCS.

Well position	Depth	Geothermal gradient, °C·m^{-1}	Seafloor temperature, °C	NGH thickness. m
TX-1	2100	42	2.4	244.07
PR-2	2000	78	2.5	486.77
QD-3	2000	77	2.5	238.29
WA-4	1050	21.5	4.1	500
ZM-5	1150	42	3.7	329.55
BK-6	1700	21.5	2.8	500
BS-7	2050	21.5	2.5	500
PW-8	2000	80	2.5	237.98
ZJ-9	2500	37.45	2.1	500
LY-10	1500	35	3.1	484.22
NW-11	1800	50	2.7	377.52
YG-12	110	33	21.1	0

(GMGS3) and 2016 (GMGS4) respectively, and obtained various NGH samples in the forms of nodules, veins, and dispersions (Wu and Wang, 2018). The natural gas of the NGH originates from source rocks of Paleogene Enping Formation and Wenchang Formation, and Neogene Zhujiang Formation and the Hanjiang Formation (Liu et al., 2012), which migrates upwards through unconformities, faults, gas chimneys, and mud diapirs. Thickness of the GHSZ is between 110 m and 320 m, while the strata-bearing NGH is between 10 m and 80 m. The NGH saturation is between 10% and 70%, and the reservoir porosity range from between 33% and 35%. The natural gas with the NGH in the Shenhu Area is a mixture of deep thermal-degraded gas and biodegraded gas, and the methane ratio accounts for more than 99% (Liu et al., 2012). The GMGS6 voyage drilling test layer is argillaceous siltstone, indicating that the NGH in the argillaceous siltstone can be effectively and safely exploited (Ye et al., 2020) (Fig. 6). Based on the above drilling surveys, 45 effective thickness data and 786 groups of porosity and saturation data obtained from exploration wells can be utilized to evaluate the NGH resource.

3.2. Evaluation principles and key parameters for in-situ NGH resource evaluation

This study uses the volumetric method to evaluate NGH resources, and the principles was introduced by Pang et al. (2021). The in-situ NGH resource can be obtained by combing the following Eq. (6) and the above obtained key parameters.

$$\mathrm{RIP} = S_{\mathrm{GHSZ}} \times K_{\mathrm{GH-S}} \times H_{\mathrm{GHSZ}} \times K_{\mathrm{GH-H}} \times P_{\mathrm{GH}} \times S_{\mathrm{GH}} \times E \times R_{\mathrm{GH}} \quad (6)$$

where RIP is in-situ NGH resource amount, m^3; S_{GHSZ} is NGH distribution area, m^2; $K_{GH\text{-}S}$ refers to area coefficient of NGH in the GHSZ; H_{GHSZ} is effective thickness of the GHSZ, m; $K_{GH\text{-}H}$ is thickness coefficient of the NGH in the GHSZ; P_{GH} is porosity of NGH reservoir, %; S_{GH} is NGH saturation, %; E is NGH volumetric ratio; R_{GH} is NGH resource coefficient obtained in the Shenhu Area, referring to the percentage of the total NGH that is enriched for recoverable resource.

When utilizing the volumetric method to estimate the in-situ NGH resource, the key parameters includes effective distribution area, effective thickness, effective reservoir porosity, NGH saturation, and NGH surface volumetric multiplication rate. In the study, the evaluated in-situ resources are corrected by area coefficient, thickness coefficient, and resource ratio coefficient of the NGH, thus the obtained in-situ resources are much more objective.

3.3. Key parameter sources and changing characteristics

Utilizing volumetric method to evaluate NGH resource in the SCS requires 8 key parameters (Eq. (6)). Among them, the area and thickness of the GHSZ (Qin et al., 2020; Yang et al., 2017) were determined by phase equilibrium analyses, with an area of 550,000 square kilometers and a thickness of 282.2 m respectively. The area ratio coefficient of NGH in the GHSZ of the SCS was determined based on BSR area identified by seismic data and the actual NGH distribution area identified by drilling wells in the Shenhu Area. For example, the Shenhu Area covers an area of 3000 km^2, and the initial BSR area identified by seismic data accounts for 727.7 km^2. By drilling 5 wells, the NGH distribution area was identified as 353 square kilometers. After drilling 19 wells, the NGH distribution area was further identified as 22 km^2 (Pang et al., 2021). Therefore, the calculated area ratio coefficient of NGH varies between 22/3000 and 728/3000, with an average of 353/3000 (Fig. 7a). The other 6 parameters, including GHSZ thickness, NGH-bearing thickness, porosity, NGH saturation, effective thickness ratio, resource ratio, are shown in Fig. 7b to g. And the first four parameters were identified from the well drilling data in the Shenhu Area, and the volumetric multiplication coefficient was derived from previous studies (Boswell and Collett, 2011; Wang et al., 2010; Fang et al., 2001).

The NGH effective thickness of the GHSZ ranges from 10 m to 800 m, with a mode of 250 m and an average of 282.2 m (Fig. 7b). The NGH thickness ratio coefficient ranges from 0.001 to 0.10, with a mode of 0.035 and an average of 0.046 (Fig. 7c). The NGH reservoir porosity ranges between 15% and 60%, with a mode value of 40% and an average of 45% (Fig. 7d). The NGH saturation mainly ranges from 1% to 50%, with a mode value of 28% and an average of 22% (Fig. 7e). The hydrate volumetric ratio ranges from 140 to 173, with a mode value of 164 and an average of 163 (Fig. 7f). The resource ratio ranges from 0 to 0.9, with an average value of 0.4 (Fig. 7g).

3.4. Monte Carlo simulation and parameter determination

Monte Carlo simulation is to simulate the probability and statistical model of a given problem by using sampling sequences of differently distributed random variables, so as to obtain approximate statistical values for the numerical solution (Zeng et al., 2006). When using the Monte Carlo simulation to evaluate resource amount, the parameters are no longer fixed values but as variables with a certain range of values (Luo et al., 2014). The large number of parameters obtained from well drilling data provide a guarantee for evaluating NGH resource more objectively. This study defines the recoverable NGH resources as follows: cumulative reservoir

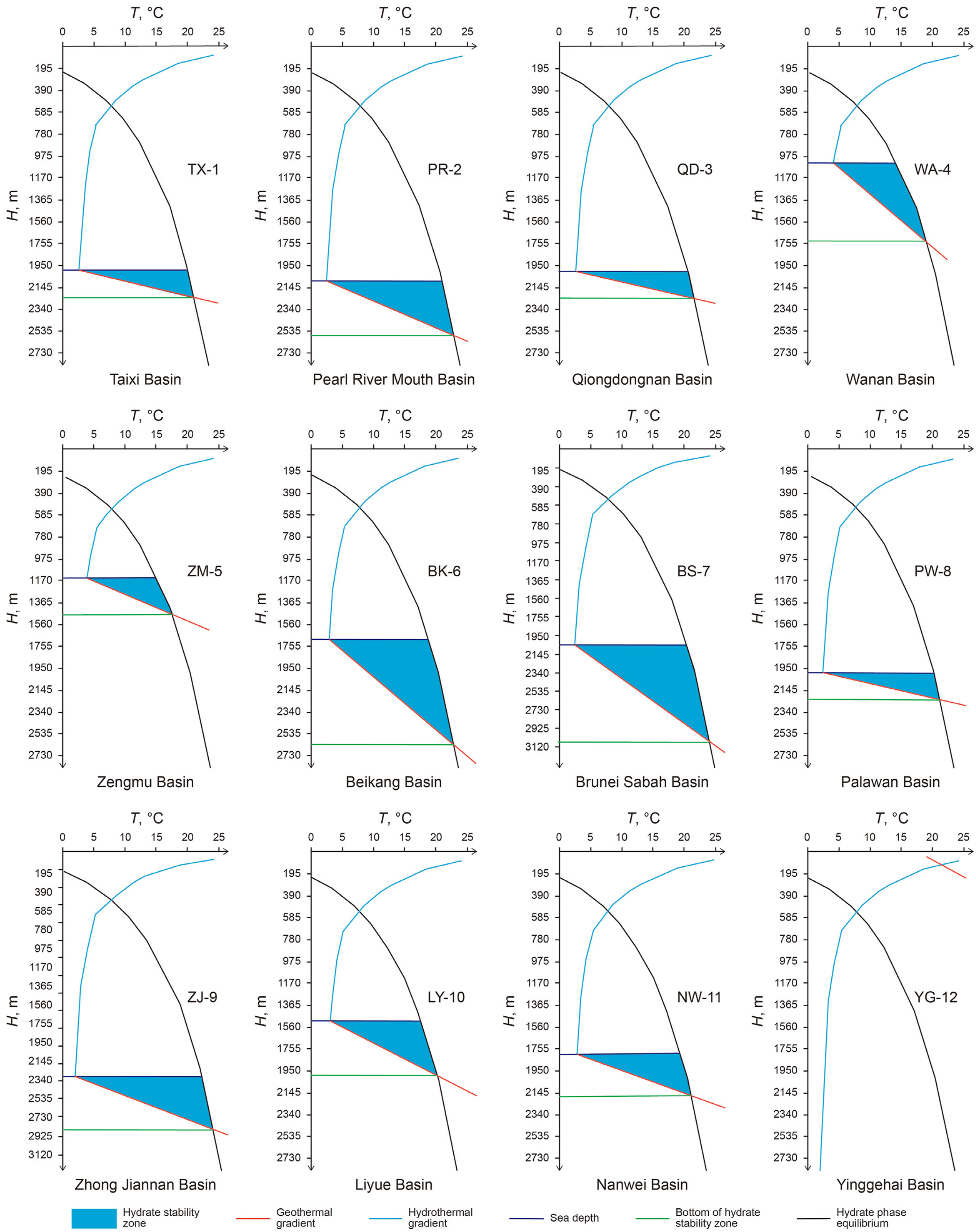

Fig. 4. Distribution characteristics of hydrate phase equilibrium at virtual well points in 12 main basins in the South China Sea.

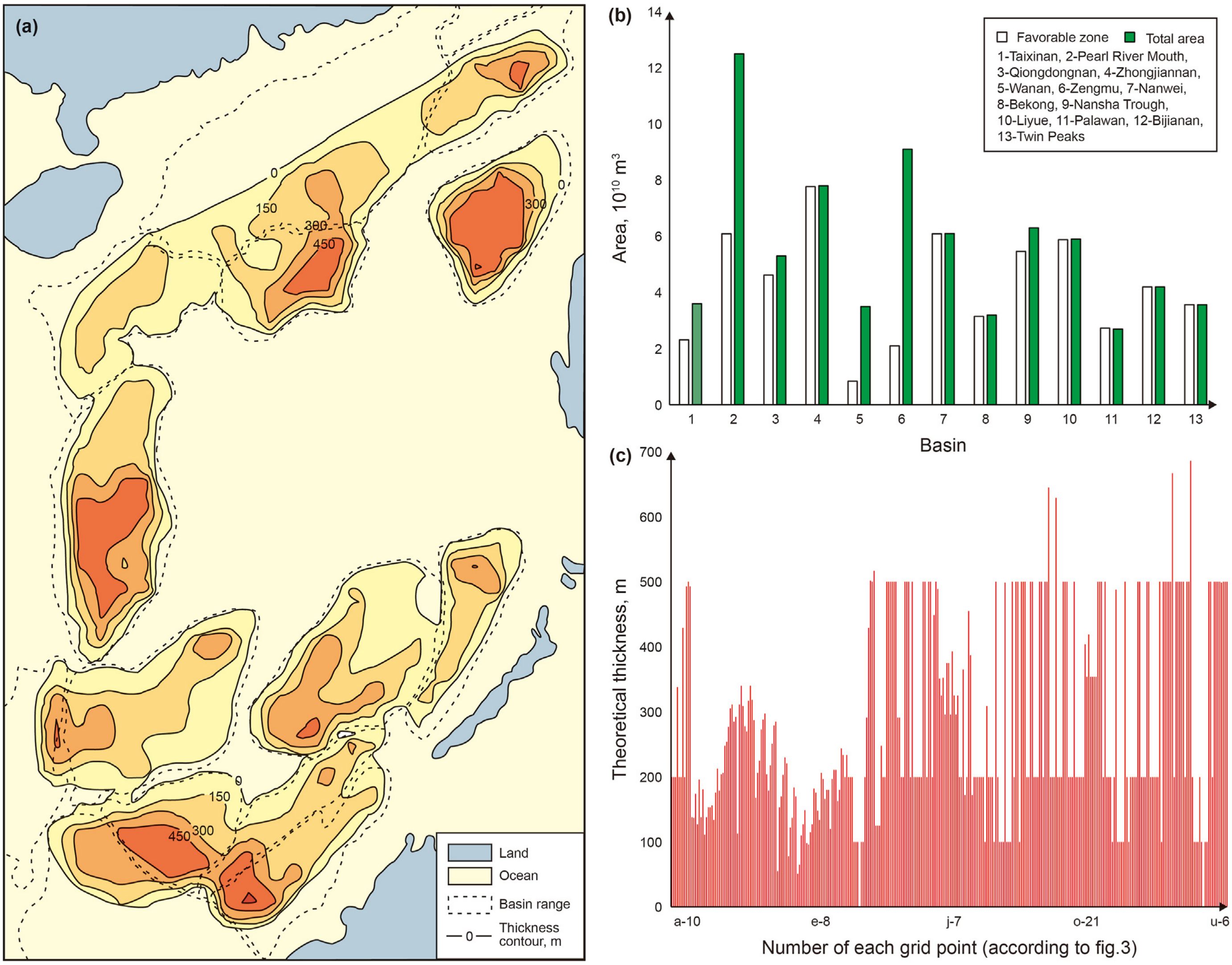

Fig. 5. Prediction results of gas hydrate distribution in the South China Sea. a. Plane distribution characteristics of the thickness of GHSZ; b. Comparison between the total areas of 12 basins and their gas hydrate distribution areas; c. Theoretical calculation results of the thickness of the gas hydrate stability zone at each grid point.

thickness (H_{GH}) > 2 m, porosity (P_{GH}) > 12%, NGH saturation (S_{GH}) > 20%. The parameter value ranges are shown in Table 3.

3.5. *In-situ resource simulation and recoverable resource estimation*

To estimate the in-situ NGH resources in SCS, a total of 1,000,000 assessments were performed using the Monte Carlo simulation. Results show that, the in-situ NGH resources with cumulative probabilities of 10%, 50%, and 90% are 2.0 × 10^{12} m^3, 7.7 × 10^{12} m^3, and 26.6 × 10^{12} m^3 respectively (Fig. 8), with a mode value of 1.9 × 10^{12} m^3 and an average of 11.7 × 10^{12} m^3.

The in-situ resources that can be mined under current techniques are technically recoverable resources (TRR). The correlation between TRR and in-situ resources is shown in Eq. (7), where K_{RE} is the recovery factor (Boswell and Collett, 2011). Currently, no NGH reservoir was explored commercially globally. Therefore, this study evaluates the recoverable NGH resource based on the recovery factor obtained by physical and numerical simulation, with maximum, minimum, and mode values of 70%, 15%, and 30% (Boswell and Collett, 2011; Collett et al., 2010; Merey and Sinayuc, 2016).

$$\mathrm{TRR} = \mathrm{RIP} \times K_{RE} \tag{7}$$

where TRR refers to technically recoverable resources; RIP refers to in-situ NGH; K_{RE} refers to recovery factor. Fig. 9 shows the REE of NGH in the SCS. The REE of NGH resources with cumulative probabilities of 10%, 50%, and 90% are 0.6 × 10^{12} m^3, 2.8 × 10^{12} m^3 and 10.3 × 10^{12} m^3 respectively, with a mode value of 1.0 × 10^{12} m^3 and an average of 4.5 × 10^{12} m^3.

4. Discussion

The evaluated in-situ NGH resource in the SCS in this study are much smaller than the average (60 × 10^{12} m^3 to 90 × 10^{12} m^3) (Zeng et al., 2006) of the previous 35 estimates, which is about 13%–20% of the average. However, the estimate obtained in this study has a higher level and is able to guide further NGH exploration with less geological risks, which is mainly because that the NGH area ratio coefficient and thickness ratio coefficient were

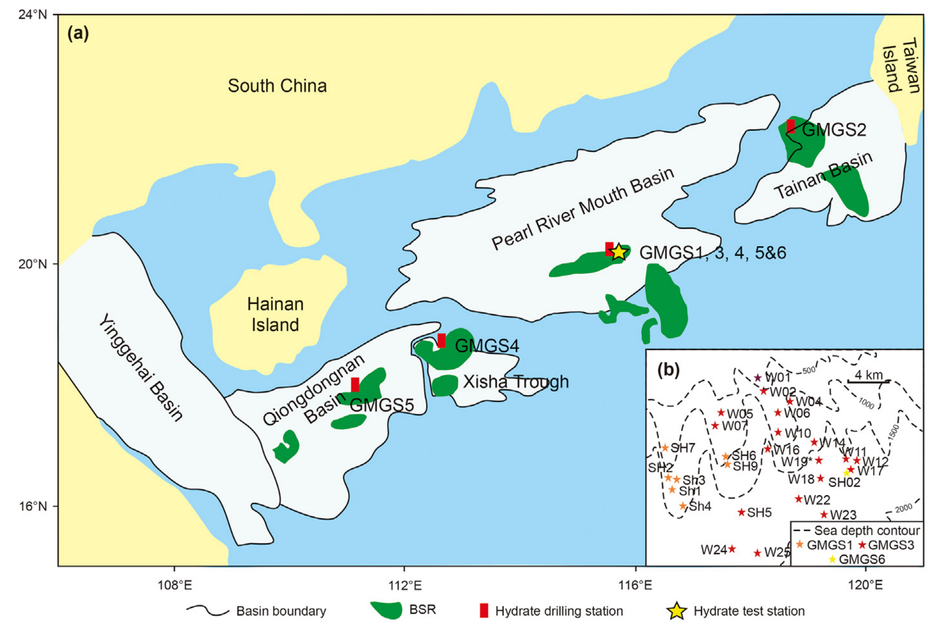

Fig. 6. (a) Geological survey location for 6 voyages in the South China Sea; (b) Overview of natural gas hydrate drilling in the Shenhu exploration area and surrounding areas (modified from Wu and Wang, 2018).

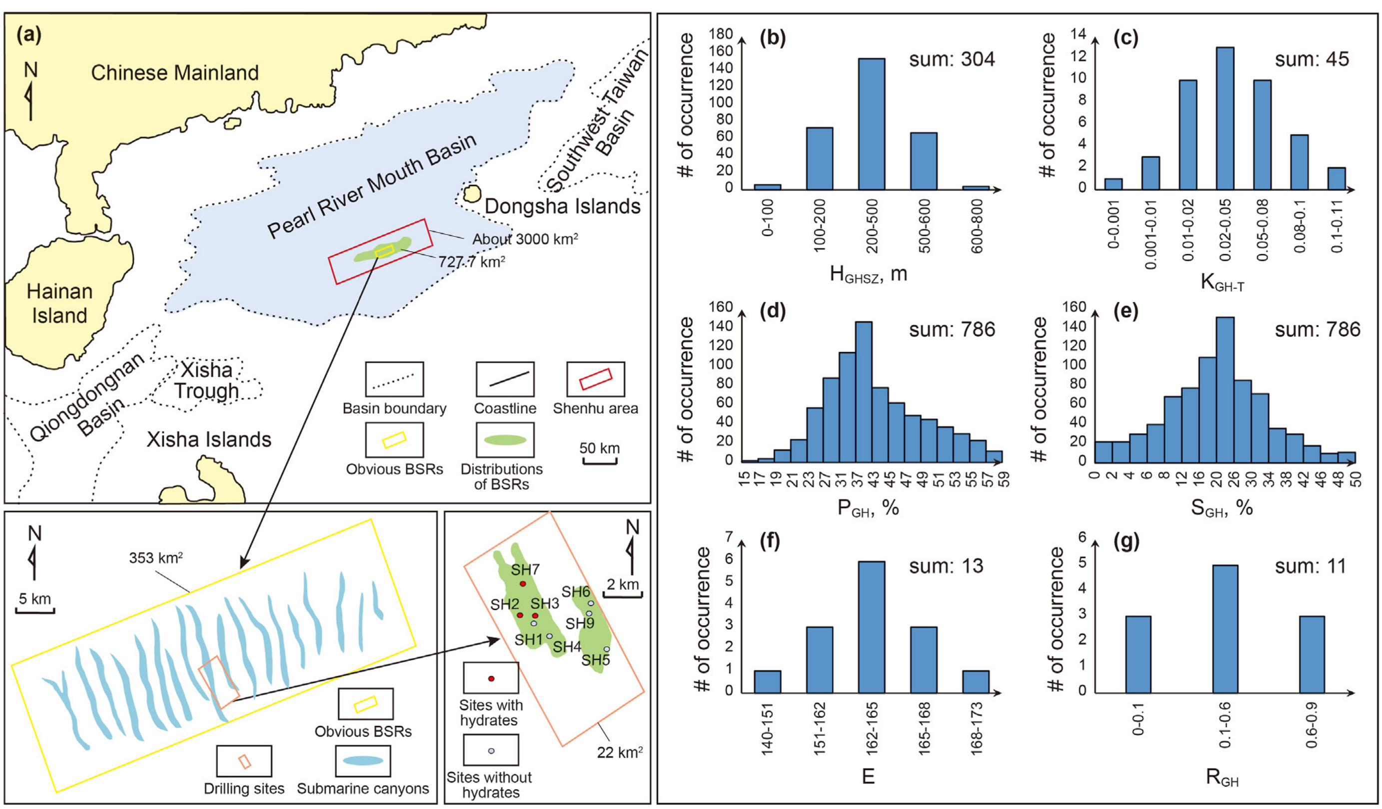

Fig. 7. The characteristics of natural gas hydrate-bearing area changes in the Shenhu exploration area of the Pearl River Mouth Basin in the South China Sea (modified from Fang et al., 2001) and the statistics of related geological parameters. a. Hydrate area change characteristics; b. Stable zone thickness; c. Hydrate thickness ratio; d. Reservoir porosity; e. Hydrate saturation; f. Hydrate volumetric ratio; g. Hydrate resources ratio.

considered on the plane and longitudinal respectively, and also considered the NGH resource ratio coefficient in three-dimensional space. The estimate is in-situ resource rather than prospective gas resource.

The estimate in this study may still be larger than the actual resources. First, when assess the in-situ NGH resource, this study did not remove the thin layers with cumulative thicknesses less than 2 m. Second, the coefficient of the resource ratio used in this

Table 3
Key parameters and their value ranges for the evaluation of hydrate in-situ resources in the South China Sea.

Parameter	Symbol	Unit	Number	Min	Max	Mode	Average (Median)
Hydrate stability zone area	S_{GHSZ}	m^2	1	–	–	–	5.5×10^{11}
Hydrate area coefficient	$K_{GH\text{-}A}$	–	3	0.007	0.242	0.117	0.117
Thickness of hydrate stability zone	H_{GHSZ}	m	304	51	686	200	282.158
Hydrate thickness factor	$K_{GH\text{-}T}$	–	45	0.003	0.156	0.044	0.046
Hydrate reservoir porosity	P_{GH}	%	786	15.88	63.0	27.952	38.957
Hydrate saturation in the reservoir	S_{GH}	%	786	20.0	55.84	21.96	29.668
Hydrate volumetric ratio	E	m^3/m^3	13	121.5	180	164	162.75
Hydrate resource ratio coefficient	R_{GH}	–	11	0.107	0.935	0.413	0.413

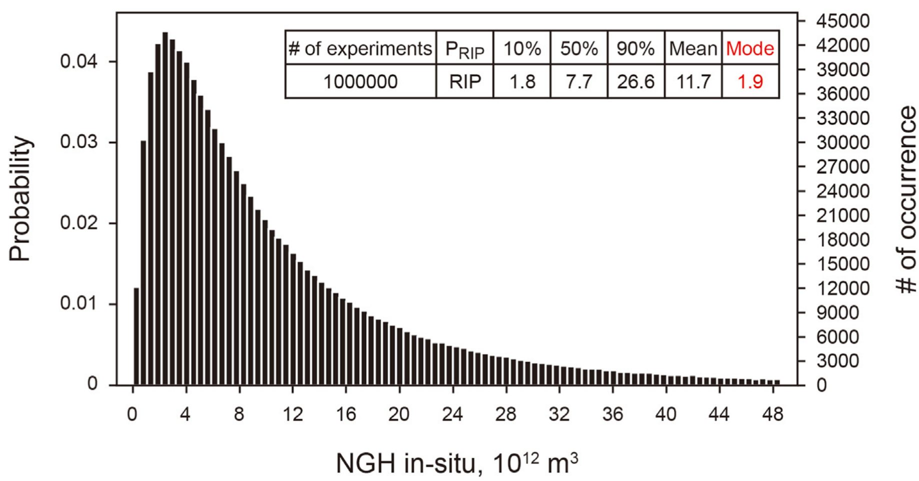

Fig. 8. Monte Carlo simulation results of in-situ natural gas hydrate resources in the South China Sea.

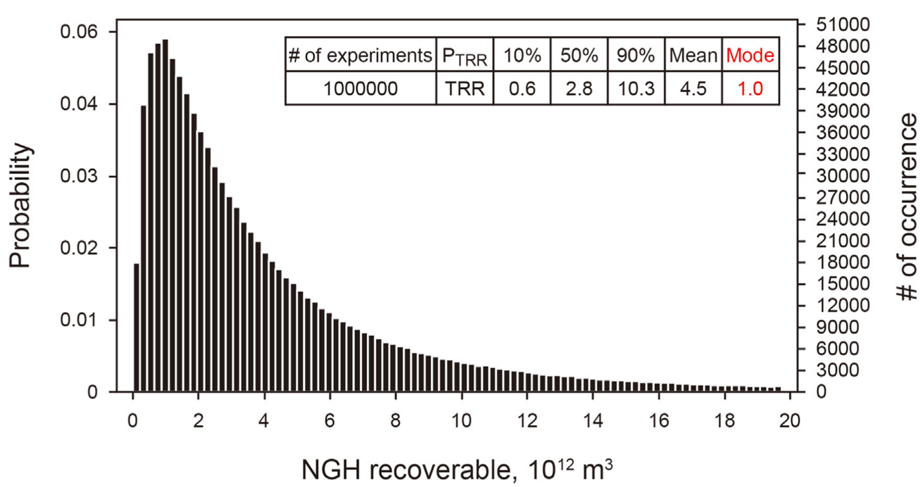

Fig. 9. Monte Carlo simulation results of recoverable natural gas hydrate resources in the South China Sea.

evaluation varies from 0.1 to 0.9, with a mode value of 0.4, which is significantly larger than the averages in previous studies (0.18–0.20) (Boswell and Collett, 2011; Boswell and Collett, 2011; Pang et al., 2021). Thirdly, the utilized recoverable coefficient was based on laboratory simulation, with a range of 15%–70% and a mode of 30%, which was higher than the recoverable coefficient for unconventional shale oil and gas (oil 7.5%, gas 20%) and tight oil and gas (oil 15%, gas 37%). Fourthly, this study only considered the technical recoverability rather than commercial availability, especially didn't consider the environmental pollution and secondary geological disasters that may be caused by large-scale exploitation. If these factors are taken into consideration, the NGH resources will be further reduced.

More accurate NGH resource evaluation requires more in-depth geological surveys of medium-shallow oil and gas. The United States, China, Japan, India and other countries have successively carried out large-scale NGH researches. However, among the top 10 well-known NGH research projects led by the United States, eight focused on the genetic mechanism, distribution rules, and resource evaluation. Even though the other two concentrated on engineering projects such as drilling investigation and trial production, their main goal is to prove the recoverability and reliability of the NGH resource. China has conducted more than 25 large-scale projects, most of which were concentrated on the engineering fields, such as drilling engineering and mining or related geological researches, with no special projects dedicated to the evaluation theories and methods about NGH resource. As a result, we have been using the classical methods in resource evaluation for many years, and the estimates and understandings are lagging behind the current world level. The fundamental way to improve the current situation is to carry out in-depth basic researches on formation condition, genetic mechanism, distribution law, and resource potential of NGH in the SCS, and figure out the objective NGH resource potential with various methods. Only when the NGH resources are evaluated objectively, the oil and gas resources in the SCS can be explored and developed effectively, and finally realize the ultimate goal of resource service for social development.

5. Conclusion

(1) Previous estimates of NGH resources in the SCS are as high as 60 to 90 $\times$ 10^8 m^3, but they are only prospective gas resource rather than in-situ resource. These previous estimates did not consider the NGH enrichment and technical recoverability, and therefore are not appropriate for guiding NGH exploration and development strategies.

(2) Based on the latest global research progress and key parameters obtained by NGH drilling wells in the Shenhu Area, SCS, this study evaluated the in-situ NGH resources, with a mode of 1.9 $\times$ 10^{12} m^3 and an average of 11.7 $\times$ 10^{12} m^3, by combing volumetric method and the Monte Carlo simulation.

(3) By coming the recovery factor obtained from physical and numerical in the laboratory and Monte Carlo simulation, and in-situ NGH resource, the technically recoverable resources of NGH are estimated, with a mode of 1 $\times$ 10^{12} m^3 and a mean of 4.5 $\times$ 10^{12} m^3. Taking environmental pollution and secondary geological disasters into account, the actual NGH recoverable resources is likely further reduced.

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