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Original Paper

Research progress and challenges of natural gas hydrate resource evaluation in the South China Sea

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A R T I C L E I N F O

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A B S T R A C T

As an efficient clean energy, natural gas hydrate (NGH) has become a hot topic in recent researches. Since 1990s, China has made great achievements and progress in NGH exploration in the South China Sea (SCS), including determination of the favorable distribution areas and favorable strata thickness, identification of the dual source for accumulation, evaluation of the prospective gas contents, verification of the widespread existence, and confirmation of the technical recoverability of NGH resources. However, there are three major challenges in the NGH studies. First, all the 24 national key and major projects in the SCS focused on trial production engineering and geological engineering in the past 20 years, while 8 of the 10 international NGH research projects focused on resource potential. Second, resource evaluation methods are outdated and some parameter selection are subjective. Third, the existing resource evaluation results are low-level with a great uncertainty, and cannot be used to guide NGH exploration and production or strategic research. To improve the evaluation of NGH resources in the SCS, future researches should focus on four aspects: (1) improve the research on the criterion of the objective existence of NGH and the method of prediction and evaluation; (2) apply new theories and methods from the global NGH research; (3) boost the research on the difference and correlation of the conditions of hydrocarbon migration and accumulation in different basins; (4) innovate the theory and method of NGH resource potential evaluation.

1. Introduction

Natural gas hydrate (NGH), commonly known as "combustible ice", is a solid natural energy formed by the combination of natural gas and water at low temperature and high pressure, which widely presents in poles of the earth, marine deep-water and plateau permafrost (Xiao and Zhang, 2021; Collett, 2002). With the development of new energy and unconventional oil and gas resources such as shale oil (Wang et al., 2020, 2021a, 2022; Hu et al., 2018, 2021, 2021b) in recent years, as a type of widely distributed and large-scale efficient clean energy, NGH has become a hot topic globally. Since the discovery of NGH, many countries have devoted great efforts to the exploration and development (Lei and Zheng, 2001; Sun et al., 2018; Zhang et al., 2014a; Zheng, 2001; Demirbas, 2010). For instance, the U.S. Senate officially listed NGH as a strategic energy source for national development in the National Long-term Plan in 1998; Japan launched the Japan Methane Hydrate R&D Program (MH21) to study the economic development and utilization of NGH in 2001 and India's Ministry of Oil and Gas implemented the National Gas Hydrates Program (NGHP) in 1997. In the past two decades, at least 29 groups of scientists or national institutions have evaluated the global NGH by different methods and technologies. The estimated amount shows a decreasing trend in time with the latest estimate in 2020 and is less than one ten-thousandth of the initial evaluation results in 1973 (Pang et al., 2021) (Fig. 1). The researches on NGH in China started in the

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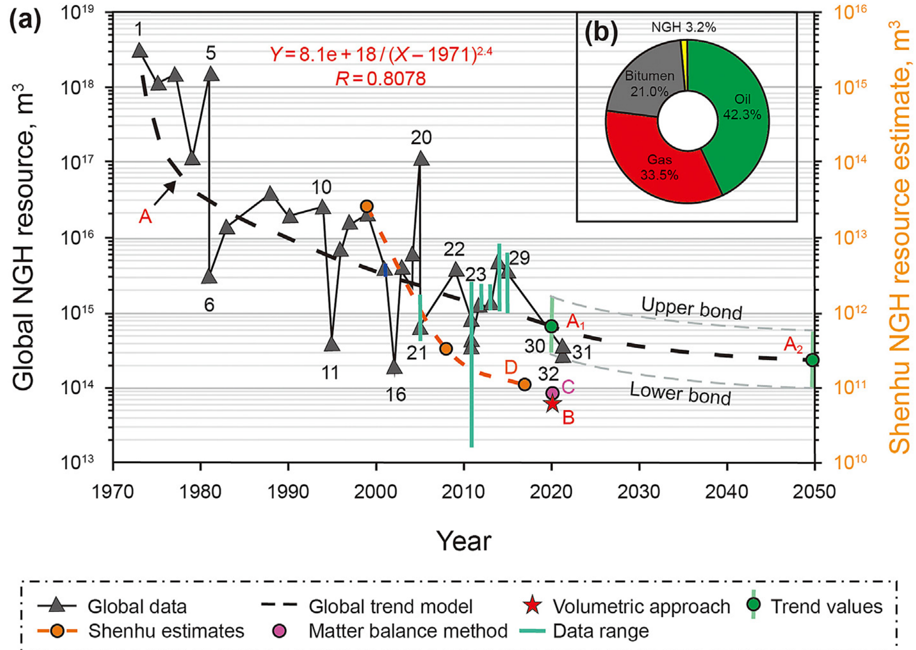

Fig. 1. Estimated results of the global resource of NGH by trend analysis method and compared to other results (Pang et al., 2021): (a) Historical global GIP estimates of NGH showing a general tendency of decreasing resource with time (A), superimposed with fitted statistical trends to project future estimates, projected resource estimates of mode values for RIP of NGH at 2020 and 2050 and their uncertainty range from the statistical trend analysis are added to the plot (A_1, A_2). The estimate of mode value for RIP of NGH from volumetric approach is shown in red star (B) and the average value for the RIP of NGH from matter balance approach is shown in pink dot (C). The historical resource estimates for GIP of NGH from 1999 to 2017 in Shenhu area of SCS are plotted to show the learning curve in brown dotted line (D); (b) The proportion of global TRR of NGH in the total amount of four types of conventional oil and gas resources is shown in the pie chart at the upper right.

early 1990s (Zhang, 2010) and since the first discovery of bottom simulating reflector (BSR) in the northern SCS in 1999 (Xiao et al., 2021), the research on hydrate in the SCS has rapidly grown, meanwhile, the SCS has been recognized as one of the most favorable NGH accumulation areas in the world. The international community and the Chinese government have both placed high hopes on the exploration and development of NGH resources in SCS.

In the past 20 years, Chinese government has put significant resources to the exploration and development of NGH in SCS, during which the trial production had been conducted in SCS and large-scale explorations are in preparation. The Guangzhou Marine Geological Survey has carried out six voyages of explorations and test exploitation projects (Fig. 2), including two voyages of drilling in the Shenhu Sea Area in 2007 and in the eastern Pearl River Estuary in 2013 (Zhang et al., 2014c, 2014b), in which 26 stations were

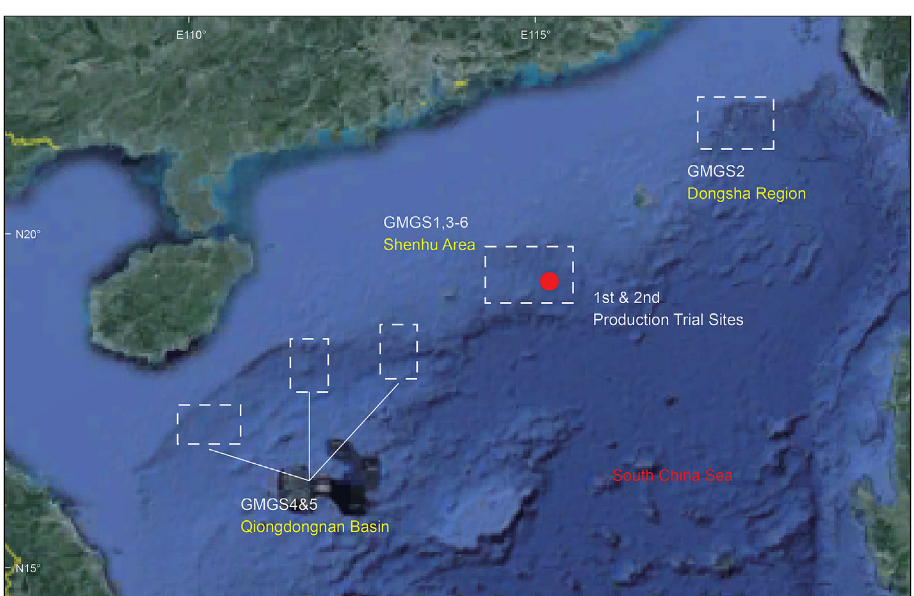

Fig. 2. Location of drilling sites of all drilling expedition during GMGS1–GMGS6 and two production trial sites (Liu and Li, 2021; Wei et al., 2019)

arranged, and 12 of them produced gas hydrate samples successfully (Wu and Wang, 2018; Zhang et al., 2014c). In addition, two drilling tests of vertical and horizontal wells were conducted in the Shenhu Area in 2017 and 2020, which were the first time for successfully and safely vertical and horizontal well trial production respectively. (Li et al., 2018; Editorial department, 2020). On November 6, 2017, NGH was approved by the State Council of China and recognized as a new energy mineral officially (report from Xinhuanet, 2017). Despite of the successful trial production, the NGH exploration in the SCS is still facing many challenges.

2. NGH evaluation progress in SCS

Previous researches and exploration have proved the wide presence of NGH in the SCS (Zhang et al., 2014b; Zhang et al. 2014c). Significant progress has been made in the determination of the favorable distribution areas, favorable formation thickness, gas source, prospective gas content and technical recoverability, which significantly improved the understanding of NGH formation and distribution and further inspired researches on new theories and methods for resource evaluation (Liu et al., 2021; Pang et al., 2021; Wang and Hu, 2021b; Zhang and Hu, 2021), and laid the foundation for re-evaluating NGH resource potential in the SCS.

2.1. Geological survey and geophysical exploration

In 1999, the Guangzhou Marine Geological Survey (GMGS) conducted a preliminary investigation of NGH resources in the Xisha Trough, which opened a new stage of NGH research in the SCS (Zhang et al., 2007). In the following 20 years, the Chinese government increased the investment on basic researches on NGH in the SCS, and supported lots of major projects through the National Natural Science Foundation of China and the National Key Research and Development Program of the Ministry of Science and Technology. From 2010 to 2020, more than 80 projects on NGH in the SCS have been completed by the National Natural Science Foundation of China with a total funding of more than 85 million Chinese yuan. In addition, a lot of practical exploration had been carried out. For example, GMGS and other institutions have carried out a lot of field exploration work in SCS from 2007 to 2020 (Zhang, 2014d), produced high-resolution multi-channel seismic survey with an area of 167000 km^2, established 4244 geological sampling stations and more than 80 drilling evaluation wells. Since the 20th century, researches about the NGH in SCS has shown a significant increasing publications, including researches about drilling and production equipment for NGH resources, test production technology, NGH formation conditions and accumulation mode, etc.

NGH exploration in the SCS can be divided into three stages, including the seismic survey stage, the drilling stage, and the trial production stage. In 1999, the BSR, a geophysical marker for the existence of NGH, was first found in the Dongsha, Shenhu, Qiongdongnan and Xisha Waters on the northern slope of the SCS. In 2007, NGH was successfully drilled in the Shenhu Area for the first time. In 2017, the trial production was successfully conducted in the Shenhu Area for the first time (Li et al., 2018), which was the longest continuous gas production time and the largest gas volume in the world at that time, proving the feasibility of safe NGH exploitation.

Fig. 3a shows the number growth of NGH research papers in the SCS, reflecting the rapid development of relevant researches, while Fig. 3b shows the differences in major NGH research projects between the SCS and abroad. Among the 24 major projects (Table 1) on NGH study in the SCS, five were about the genetic mechanism and geological conditions of hydrate and the others were on drilling and production engineering, with no systematic research on NHG resource evaluation. This is completely contrary to the fact that only 2 of the 10 major research projects (Table 2) led by foreign governments were drilling and production engineering but 8 were concentrated on NGH resource evaluation, which highlights the urgency of conducting NGH resource evaluation in the SCS.

2.2. Favorable NGH distribution area and strata thickness prediction

Favorable NGH distribution area was mainly determined by the BSR method (Liang, 2006; Wang et al., 2005; Ge, 2006), which is applicable to a wide area of different geological conditions but has low accuracy. By using BSR method, Yao (2001) estimated the favorable area for NGH formation in the SCS was 93 $\times$ 10^4 km^2. The favorable area was further constrained by drilling conditions, updated water depth, seabed temperature and geothermal gradient, and Hydrate Gas Stability Zones (GHSZ) predicted by the NGH phase equilibrium mechanism. After taking these constraints into account, with the progress of trial production and the increasing logging data and NGH hydrate samples, the prediction accuracy of the favorable area was further improved. The Shenhu Area is one of the key research areas in the SCS and its NGH resource evaluation began in 1999, when a favorable area of about 3000 km^2 was estimated based on BSR method. In the next eight years, with the newly collected data from the trial exploration, the favorable area was gradually reduced to a range of 22–600 km^2, with an average of 300 km^2, which is one tenth of the first evaluation (Su et al., 2014) while the NGH distribution was determined with high precision. For the whole SCS, the estimated favorable areas are from 11.2 to 330 $\times$ 10^4 km^2, with an average of 66.5 $\times$ 10^4 km^2.

There are two methods for calculating the NGH thickness. One is based on seismic data, phase equilibrium equation and corresponding pressure-temperature equation, and the other one is based on exploration data such as logging while drilling borehole images log (GVR) (Yang et al., 2017). Due to low exploration level, the estimation of the favorable strata thickness in the SCS is mostly based on the first method. Xu et al. (2010) calculated the thickness of GHSZ in the SCS by using the temperature and pressure equation for hydrate stability (Fig. 4a), results showed most of the NGH thicknesses were more than 100 m, which mainly distributed in the Nanwei Basin and Lile Basin in the middle and east of the SCS (Fig. 4b). The second method is suitable for the Shenhu Area, where actual logging data and coring data were available, and the effective thickness evaluation results are much more reliable. Yang et al. (2017) analyzed the data of 19 wells in the Shenhu Area which included GVR in the study for the first time and counted the effective NGH thickness in each well location, and results showed the thicknesses are between 1 m and 77.3 m, with an average of 14.18 m. It can be seen that the statistical values from the logging data are much smaller than the estimated values by the first method. This is because that, the thickness determined by theoretical calculation is the overall thickness of the GHSZ, rather than the effective hydrate bearing thickness. Due to the differences in data and evaluation methods, evaluation results from different researchers show that the favorable thickness in the SCS is between 152 m and 560 m, with an average of 355.6 m. Obviously, they are much larger than the actual hydrate thickness.

2.3. NGH accumulation model

For a long time, NGH resource evaluation only considered the natural gas sources near the surface (Archer et al., 2002; Wang et al., 2018), while neglected the contribution of natural gas from the deep sources. Recently, drilling in the Shenhu Area of the SCS proved that the natural gas in the NGH samples was a mixture of

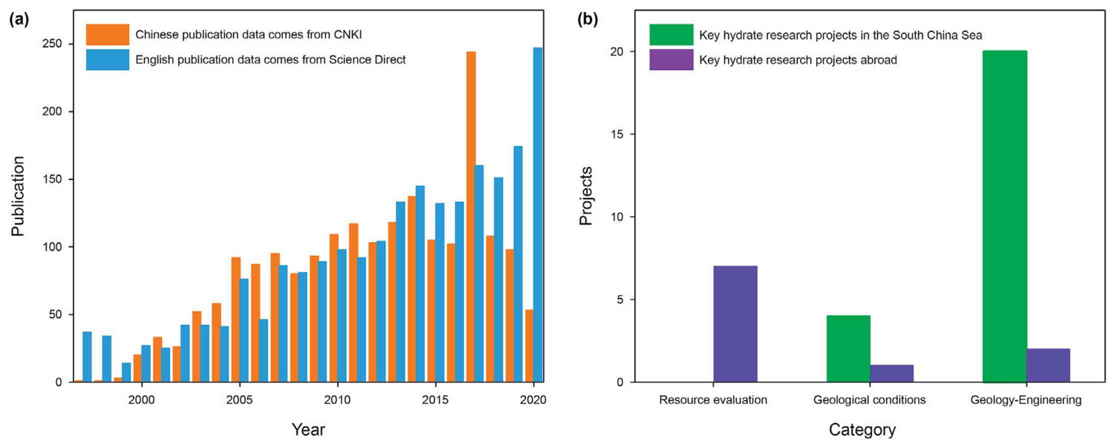

Fig. 3. The number of publications and the key research projects on NGH in China and over the world. (a) The number of Chinese and English publications on gas hydrate in the SCS (the data of Chinese publications are from CNKI; the data of English publications are from Science Direct); (b) Comparison of the research fields involved in the hydrate research projects funded by the Chinese government and by foreign governments (data source Tables 1 and 2).

Table 1
Key research projects and related fields of NGH in SCS.

	Category	Project category	Project name
1	Geological conditions	NSFC - Joint Funds	Characteristics and gas liquid solid multiphase heat and mass transfer mechanism of argillaceous silt gas hydrate reservoirs in the SCS
2	Geological conditions	NSFC - Funds for International Cooperation and Exchange	Study on the occurrence structure of natural gas hydrate in sediment porous media
3	Geological conditions	NSFC - Major Research plan	Nuclear magnetic resonance study on evaluation model and metallogenic mechanism of natural gas hydrate in sediments
4	Geological conditions	MOST - National Key Research and Development Program of China	High resolution 3D seismic exploration technology for gas hydrate
5	Geology-Engineering	MOST - National Key Research and Development Program of China	Study on reservoir forming principle and exploitation basis of multi type gas hydrate in SCS
6	Geology-Engineering	MOST -National Program on Key Basic Research Project (973 Program)	Study on gas hydrate enrichment and exploitation in SCS
7	Geology-Engineering	NSFC - Key Program	Study on decomposition mechanism and control method of natural gas hydrate
8	Geology-Engineering	NSFC - Major Program	Drilling and production mechanism and control of gas hydrate in SCS
9	Geology-Engineering	NSFC -Joint Funds	Study on thermophysical characteristics and heat transport mechanism of natural gas hydrate
10	Geology-Engineering	NSFC - Funds for International Cooperation and Exchange	Study on evolution of geomechanically parameters of gas hydrate reservoir in SCS during hydrate exploitation
11	Geology-Engineering	NSFC - Major Program	Theory of gas hydrate reservoir structure transformation and high efficiency development model
12	Geology-Engineering	NSFC - Major Program	Temporal and spatial evolution of gas hydrate phase transition and percolation in reservoir
13	Geology-Engineering	NSFC - Major Program	Mechanical characteristics and multi field coupling engineering response mechanism of gas hydrate reservoir
14	Geology-Engineering	NSFC -Joint Funds	Research on development strategy of natural gas hydrate exploration and development engineering technology
15	Geology-Engineering	NSFC - Major Program	Formation mechanism and safety control method of multiphase flow barrier in natural gas hydrate drilling and production wellbore
16	Geology-Engineering	NSFC - Major Program	Interaction and safety design between gas hydrate wells and deep sea soil
17	Geology-Engineering	NSFC - Key Program	Research on key test technology and engineering mechanical properties of soil containing natural gas hydrate
18	Geology-Engineering	NSFC -Joint Funds	Mechanism of gas hydrate formation in liquid continuous impinging stream coupled with bubbling
19	Geology-Engineering	NSFC - Key Program	Key influencing factors of energy efficiency in natural gas hydrate exploitation process and methods to improve energy efficiency
20	Geology-Engineering	NSFC - Key Program	Study on methane storage and carbon dioxide separation and storage in exploitation and utilization of marine natural gas hydrate
21	Geology-Engineering	MOST - National Key Research and Development Program of China	Trial production technology of marine natural gas hydrate
22	Geology-Engineering	MOST - National Key Research and Development Program of China	Research on safe and efficient mining mechanism and key technology of deep sea argillaceous silt gas hydrate ore body
23	Geology-Engineering	MOST - National Key Research and Development Program of China	Application demonstration of hydrate production test, environmental monitoring and comprehensive evaluation
24	Geology-Engineering	NSFC - Major Program	In situ study on formation mechanism and release mechanism of natural gas hydrate

a) NSFC: National Natural Science Foundation of China; b) MOST: Ministry of Science and Technology of the People's Republic of China.

Table 2
Key research projects of natural gas hydrate led by foreign governments and related fields.

No.	Category	Project name
1	Geological conditions	Geomechanics of the Mallik Gas Hydrate Reservoir, Mackenzie Delta, NWT
2	Geology-Engineering	Alaska North Slope 2018 Hydrate 01 Stratigraphic Test Well
3	Geology-Engineering	the Ocean Drilling Program (ODP) Leg 204
4	Resource evaluation	Results of the India National Gas Hydrate Program Expedition 02
5	Resource evaluation	Assessment of Gas Hydrate Resources in the North Slope of Alaska
6	Resource evaluation	U.S. Geological Survey Gas Hydrates Project
7	Resource evaluation	Gas hydrate field projects in the Indian Ocean, on the Alaska North Slope, and in the Gulf of Mexico
8	Resource evaluation	Deepwater Methane Hydrate Characterization in the Gulf of Mexico: Scientific Assessment and Production Potential
9	Resource evaluation	Evaluation of the Gas Production Potential of Marine Hydrate Deposits in the Ulleung Basin of the Korean East Sea
10	Resource evaluation	Research Consortium for Methane Hydrate Resources in Japan [MH21 consortium]

biodegraded and thermal gas (Zhang et al., 2017), indicating that both of the two types of natural gas contribute to the NGH formation. Based on it, a geological model of NGH accumulation from dual sources in the SCS (Fig. 5) was established, revealing that the deep thermal gas also has an important contribution. In addition, analyses of 13 NGH reservoirs in the world also showed that, three fifths of which comes from microbial degradation gas, and the rest originates from deep thermal degradation gas (Dai et al., 2017; Pang et al., 2021).

2.4. NGH resource potential evaluation

Significant progress had been made in the NGH resource potential evaluation in the SCS. Since 2001, 35 NGH evaluation was conducted in the SCS (Table 3) by utilizing volumetric method, particle organic carbon deposition rate method and comprehensive analysis method. Focuses on the distribution characteristics of NGH reservoirs, volumetric method was first proposed by Trofimuk et al. (1973), and then was used to calculate NGH resource by multiplying area, thickness, reservoir porosity, gas hydrate saturation and gas volume conversion coefficient. This method is theoretically simple, but a major defect is that it is difficult to determine the actual values of the abovementioned geological parameters objectively. Among the 35 evaluation results, 10 of which used volumetric method. The particle organic carbon deposition rate method is based on the theory that the gas source of NGH is organic carbon. The amount of gas accumulated to form NGH is controlled by the amount of gas generated and discharged from source rock. However, this method is not mature at present, mainly due to no reliable way existed to estimate the proportion of the gas generated by source rock which is lost or accumulated, and only 2 of the 35 groups used this method. The comprehensive analysis method evaluates the NGH resource by referring to previous evaluation results and the actual conditions, including correction of previous evaluation results that leads to a major defect and it can be very subjective. However, 23 of the 35 groups used this method and most of them estimated the amount of NGH within the range of 60×10^{12} to 80×10^{12} m^3, or oil equivalent of $(60–90) \times 10^9$ t (Fig. 6), which is equivalent to 80% of the total conventional oil and gas resources in China.

2.5. Large-scale NGH development feasibility confirmation

Major breakthroughs have also been made in trial productions of NGH in the SCS. In 2017, 2020, vertical and horizontal well were drilled in the Shenhu Area, and subsequent trial productions of both wells were conducted successfully (Fig. 7). The first test production was conducted by China Geological Survey from May to July 2017 (Xu and Luo, 2017), during which the NGH was successfully extracted from the undiagnostic clay silt sediments in soft strata, with a thickness of 203–277 m at a water depth of 1266 m. This is the first time both in China and world that NGH was successfully extracted from undiagnostic clay silt type sediments in shallow surface layer of a deep seabed. In this production, the maximum yield was 3.5×10^4 m^3/d, and the average yield was over 5151 m^3/d, with maximum methane content of 99.5%. The gas production was continuously stable for 7 days and 19 h, and the accumulative gas yield was 30.9×10^4 m^3. In summary, this trial production has made a number of major breakthroughs, such as long sustained gas production time, stable flow, environmental safety, etc., and also verified the technical recoverability of NGH in the SCS for the first time. The second trial production lasted 183 days from October 2019 to April 2020 (Ye and Qin, 2020), from offshore construction to demobilization of the platform, and the horizontal well drilling was tested for the first time and produced gas continuously for 30 days, with a daily yield of 2.87×10^4 m^3, which was 5.57 times of that in 2017. The total gas yield was 861.4×10^4 m^3 and the entire production process went smoothly, with no seabed deformation or methane leakage. These two trial productions confirmed the NGH technical recoverability, accumulated key technologies and experiences for NGH exploration (Table 4), and provided valuable data for further resource evaluation.

3. Problems and challenges for NGH resource evaluation

3.1. Previous studies paid a little attention on NGH resource evaluation in the SCS

There are 24 national major projects related to NGH researches in the SCS, 19 of which focus on trial production engineering (79.2%) and the rest concentrates on geological engineering, but there is little research on resource evaluation methods. Currently, the methods used in NGH resource evaluation are conventional methods for petroleum resource evaluation, although the principle is simple, the value is very fluctuating and greatly affected by human subjective factors. In comparison, there are 10 major NGH research projects led by the global government, of which 7 focus on resource potential, 1 involves geological engineering and 2 involves drilling and production engineering. Therefore, it is necessary to focus on resource potential evaluation in the initial stage of NGH researches. If we persist in large-scale exploration and development without realizing the resource potential, it may bring significant risks. In addition, the evaluation results of NGH resources in the SCS are as high as $(60–90) \times 10^9$ t oil equivalent, which is about 2–3 times higher than the total amount of 35×10^9 t of conventional oil and gas resources in the SCS, which is not in line with the mass balance principle. Moreover, the NGH evaluation results have remained unchanged in recent 20 years, which is also inconsistent with the major progress and cognitive changes in global NGH researches. Moreover, most NGH with hydrate saturation of 1%–14% and average value less than 5% are regarded as resources, which is

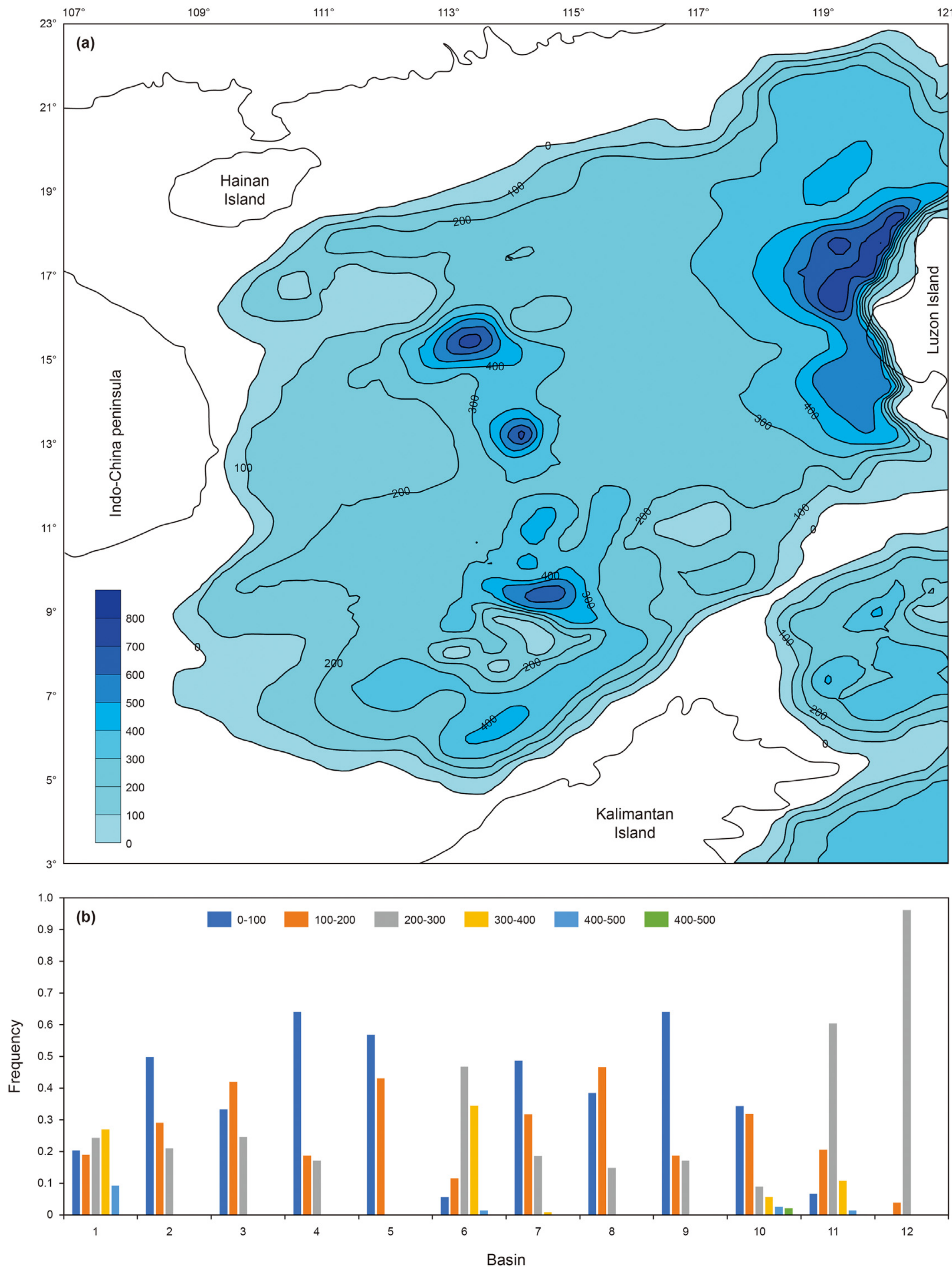

Fig. 4. Predicted stable zones of NGH in the SCS (Xu et al., 2010). (a) Thickness distribution of gas hydrate stable zones in SCS; (b) Statistical chart of NGH stable zone thickness in major basins of the SCS, data source, 1-Southwest Taiwan Basin, 2-Pearl River Mouth Basin, 3-Qiongdongnan Basin, 4-Wan'an Basin, 5-Zengmu Basin, 6-Beikang Basin, 7-Brunei-Sabah Basin, 8-Palawan Basin, 9-Zhongjiannan Basin, 10-Lile Basin, 11-Nanwei Basin, 12-Shuangfeng Basin.

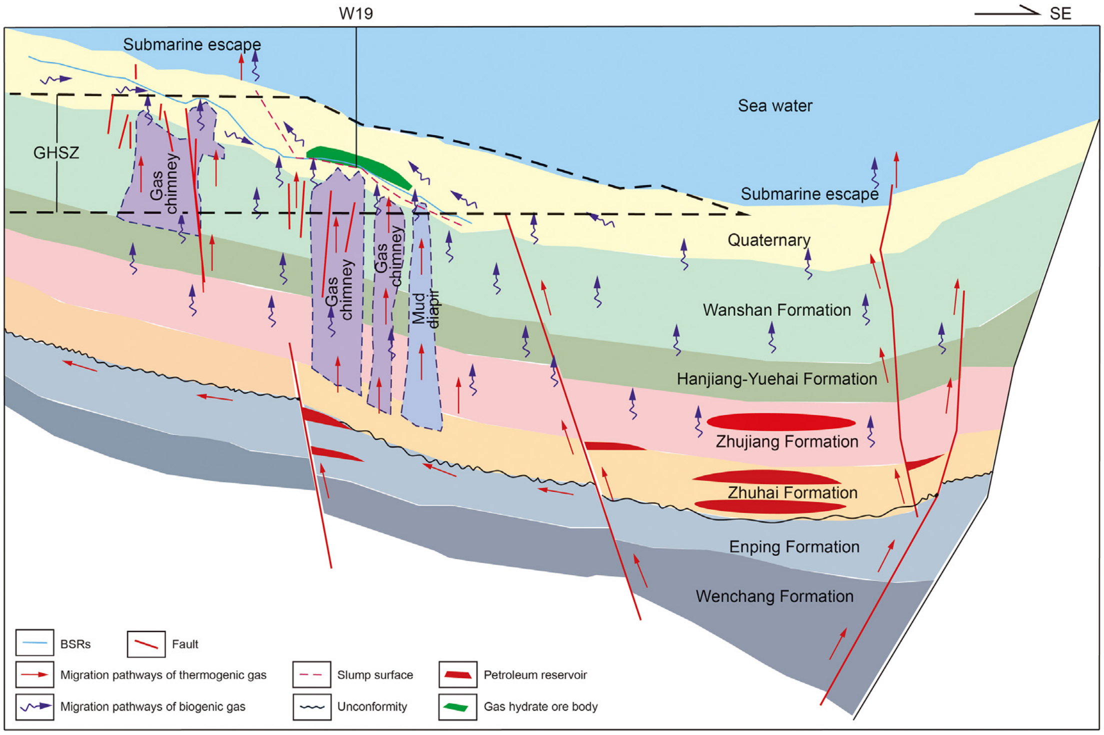

Fig. 5. Gas hydrate accumulation model in the Shenhu Area of the SCS (Zhang and Liang, 2017).

Table 3
Summary of evaluation results and key parameters of gas hydrate resources in SCS.

No.	Time	Method	Estimation of NGH, $\times 10^{13} m^3$	References
1	2001	V	6.7	Yao, 2001
2	2002	V	8.45	Zhang, 2002
3	2003	V	1.949	Zeng and Zhou, 2003
4	2004	V	6.93	Zhu, 2004
5	2005	V	2.32	Wang et al., 2005
6	2006	V	6.3	Ge, 2006
7	2006	V	6.4968	Liang, 2006
8	2006	V	6.4968	Zeng et al., 2006
9	2007	C	6.4	Yang et al., 2007
10	2008	C	6.7	Yao et al., 2008
11	2008	C	7	Qian and Zhu, 2008
12	2009	C	6.497	Zhang et al., 2009
13	2009	C	6.5	Ning, 2009
14	2009	C	6.497	Wei, 2009
15	2009	D	16.6	Huang, 2009
16	2009	V	6.92	Huang, 2009
17	2010	C	7	Hu et al., 2010
18	2010	C	7	Wang et al., 2010a
19	2010	C	7	Chen, 2010
20	2011	C	8.45	Liu et al., 2011
21	2012	V	13.8	Nguyen, 2012
22	2012	C	7	Lin, 2012
23	2013	C	6.4968	Sun et al., 2013
24	2013	C	6.5	Chen and Meng, 2013
25	2014	C	7.4	Gong, 2014
26	2014	C	6.5	Zhang et al., 2014e
27	2015	C	6.497	Wang, 2015
28	2015	C	7.0785	Fu et al., 2015
29	2017	C	7	Dong, 2017
30	2017	C	8	Liang, 2017
31	2017	C	6.8	Gao, 2017
32	2017	C	7	Zong, 2017
33	2018	C	8	Wang and Sun, 2018
34	2018	D	4.2	Wang et al., 2018
35	2019	C	6.93	Yu, 2019

a) V-Volumetric method; b) **C**-Comprehensive Analysis method; c) D-Particle Organic Carbon Deposition Rate Method.

inconsistent with the technical reality. All these show that it is of great significance for strengthening NGH resource evaluation in the SCS.

3.2. Current resource evaluation methods are outdated and parameter selection are subjective, which cannot reflect the latest NGH research progress

First, lacking detailed studies on the phase equilibrium mechanism of NGH in the SCS. NGH can only exist in geological areas with high pressure and low temperature (Fig. 8). The pressure and temperature condition theoretically determine the maximum plane range and the maximum formation thickness of the NGHs. The NGH phase equilibrium is mainly affected by the sea bottom water temperature, water depth and geothermal gradient in the strata below the sea bottom. There are 16 major basins in the SCS, including the Pearl River Mouth Basin and Qiongdongnan Basin in the northern SCS, the Yinggehai Basin in the west, the Zengmu Basin and the Brunei-Sabah Basin in the south, and the Palawan Basin in the east. The conditions for NGH accumulation in these basins are not exactly the same, leading to different phase equilibrium state and different GHSZ distribution at the same depth. At present, the NGH resource evaluation is mainly based on the parameters obtained from highly studied area, such as the northern continental slope of the SCS, to estimate the NGH resources of the whole SCS. However, parameters from the highly studied area are commonly much more promising than that of the other areas in the SCS. By using them, the estimated NGH resource amount of the SCS will be much exaggerated.

Second, the mass balance between the total amount of natural gas generation and the amount of various resources were not considered in current resource evaluation. Natural gas comes from the degradation of sedimentary organic matter, which can form either NGH or conventional gas reservoirs or both in shallow sea

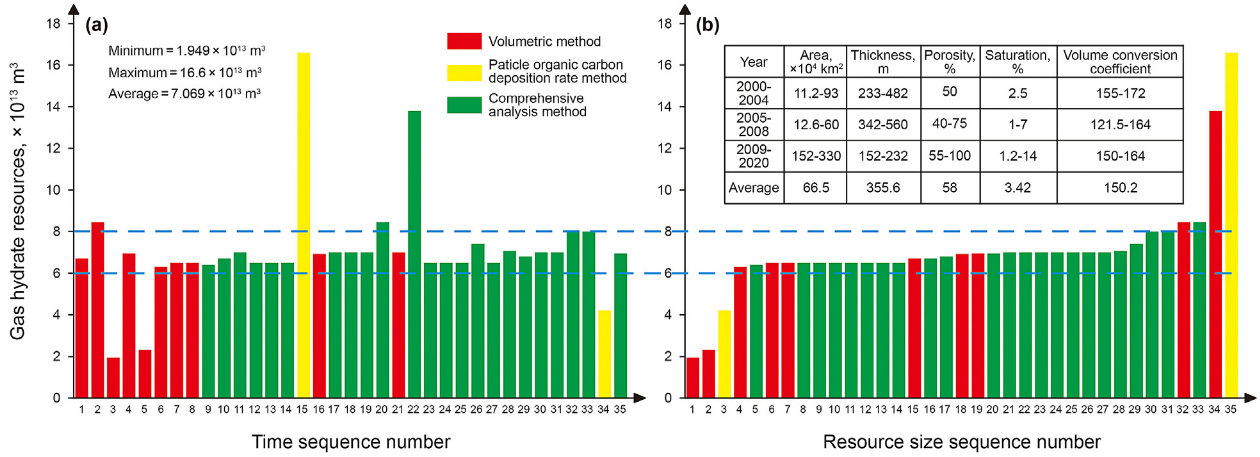

Fig. 6. Evaluation results of NGH resources potential in the SCS over the last twenty years from 2000 to 2020, data from Table 3. (a) Arrange in time order; (b) Arrange in resource size order.

Fig. 7. Two successful gas hydrate production trials in the SCS. (a) Offshore drilling gas hydrate site of the first round trial production (Xinhua News Agency, 2017), (b) The second round trial production site of natural gas hydrate in China's sea area (Trial production site, 2020).

Table 4
Results of 2 trials in the Shenhu Area of the SCS.

Times	Date	Time	Reservoir types	Drilling type	Continuous gas production time	Average daily gas production	Cumulative gas production
1	2017.5.10 –2017.7.9	60d	Mud silt reservoir	Vertical well	7d 19h	5151 m^3	30.9×10^4 m^3
2	2019.10.20 –2020.4.19	183d	Mud silt reservoir	Horizontal well	30d	28.7×10^4 m^3	861.4×10^4 m^3

bed layers. Therefore, NGH resource evaluation should not be independent from other resource evaluation studies. For a long time, natural gas in NGH was considered to derive from seawater or from an inorganic origin (Geng et al., 2003). The geochemical characteristics and carbon isotope analysis of global 13 NGH reservoirs had proved that, these NGH resources are all derived from the degradation of organic matter in sedimentary basins (Dai et al., 2017), which just like other fossil energy resources such as the oil and gas resources. Only when the natural gas is enriched in reservoirs with high porosity and permeability can it form an effective resource. This indicates that the NGH resource potential cannot exceed the total amount of fossil gas energy, as is a part of the energy system itself. However, the current NGH evaluations in the SCS does not consider the restriction from the carbon source. Without considering the source of deep pyrolysis gas, the average value of natural gas hydrate resources in the South China Sea obtained by the evaluation is more than the total biogas generation in the whole South China sea, which deviates from this restriction relationship. In detail, the average estimates of the NGH resources in the SCS is more than the total amount of biogas in the SCS. Previous studies have shown that the total amount of natural gas generated by microbial degradation in the sedimentary strata at the bottom of the SCS is about 4000 trillion cubic meters, which is only about 30% of the current resource evaluation result ((60–90) $\times$ 10^9 t of oil equivalent) (Strategic Research Center of Oil and Gas Resources, Ministry of Land and Resources,2009). Therefore, it is necessary to consider the accumulation of multi-source natural gas and the mass balance between different types of gas resources when evaluating the NGH resources. By comparing two basins with similar amount of sedimentary organic matter, the one with a larger amount of conventional resources may have less NGH resources.

Third, the contribution of deep thermal degraded gas for NGH formation was not considered in current resource evaluation. The geochemical characteristics and carbon isotopic analysis of the global 13 natural gas hydrate reservoirs (Dai et al., 2017) showed

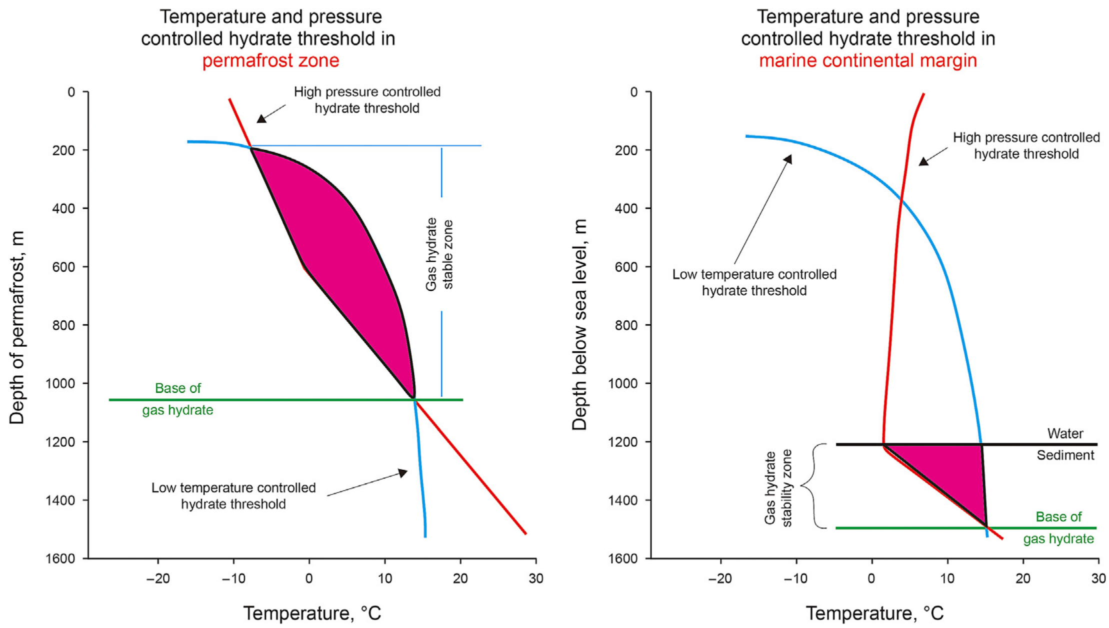

Fig. 8. Diagram of hydrate phase equilibrium model (Modified from Shaibu et al., 2021; Chong and Yang, 2016).

that the deep degraded gas contribute to two fifths of the total amount of NGH, and biodegraded gas contributes to the rest. Therefore, the NGH evaluation should consider both the shallow biodegraded gas and deep thermal degraded gas. Among the 35 groups of resource evaluation results in the SCS, two were derived from genetic method, and the two groups only considered the biodegraded gas. The main reason is that there is a lack of effective methods for evaluating deep natural gas contribution (Huang, 2009; Wang et al., 2018).

Fourth, NGH enrichment degree was not considered. NGH can only be formed as minable resources after enrichment. The resource enrichment degree is a key parameter in resource evaluation, but current studies did not fully consider it, with calculating the total NGH amount in the stable zones. It is necessary to multiply the total accumulation amount by an enrichment coefficient. The enrichment coefficient refers to the ratio of enriched resource to all accumulated resource, including the dispersed resource. It is determined by many geological conditions and also technical level for resource exploitation. For example, for conventional gas reservoirs, the amount of resources in place is usually refers to the gas accumulated in reservoirs with porosity >12%, gas saturation >40%, accumulated gas reservoir thickness >2 m, etc. In the study of global NGH resource evaluation, Boswell estimated that the enriched gas resources in place accounted for only 22% of the total gas accumulation (Fig. 9). Pang et al. (2021) calculated the enrichment factor of in-situ NGH to be 18% according to the drilling results of the Shenhu Area.

Fifth, technical recoverability of NGH was not considered in the previous NGH evaluation studies. Only part of the in-situ NGH resources can be extracted under current technical conditions,

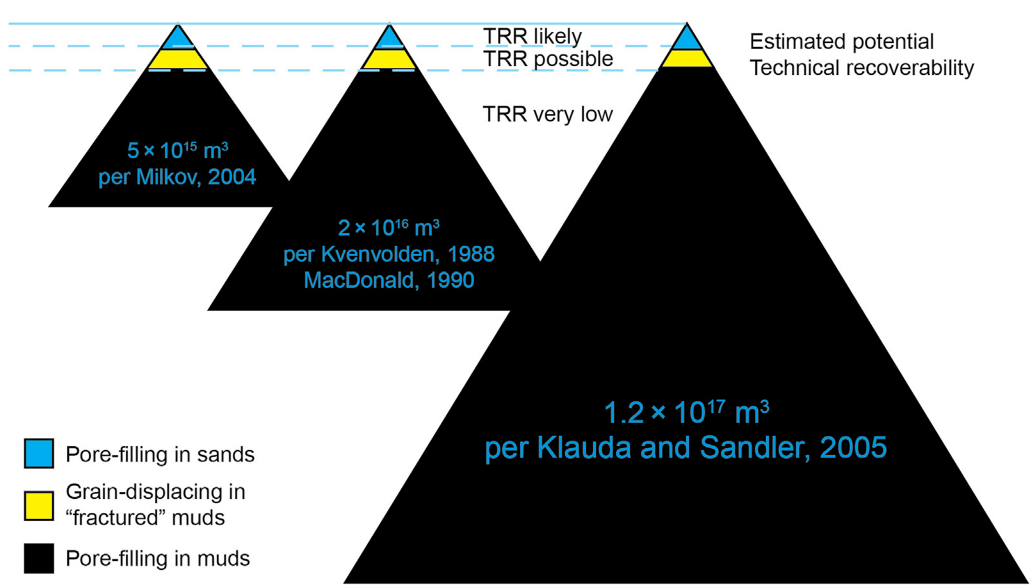

Fig. 9. Enrichment mode diagram of NGH resources (modified from Boswell and Collett, 2006, 2011; Klauda and Sandler, 2005; Kvenvolden, 1988; MacDonald, 1990; Milkov, 2004; Boswell, 2009).

which were called technically recoverable resources. The ratio of the technically recoverable resources (level V) to in-situ resources (level IV) refers to the recovery factor, which was considered in current evaluations. Herein, the in-situ NGH resource refers to resources in reservoirs with high porosity and permeability that were widely distributed under the sea or under polar and plateau ice sheets. The recoverable resources are mainly concentrated in high porous and permeable sandstone or mudstone reservoirs with fractures, and can be recovered undercurrent technical conditions (Li and Liu, 2018). Generally, for the recoverable resources, accumulated thickness is > 2 m, reservoir porosity is >12%, and hydrate saturation is >40% (Pang et al., 2021). Konno et al. (2014) obtained a hydrate recovery rate of 15%–70% with an average of 30% through a physical simulation experiment (Fig. 10). For the NGH resources in the SCS, if both the enrichment degree and the recovery factor are considered, the resource amount could be reduced by two or three magnitude orders.

3.3. Current resource evaluation results are low-level and great-uncertainty and cannot guide exploration or strategic research

First, current results of NGH resource are low-level. Generally, the conventional oil and gas resource evaluation goes through three steps. The first is to calculate the amount of oil and gas generated from source rocks after studying the generating rate of hydrocarbons from a unit mass of organic matter. The Second is to calculate the amount of oil and gas discharged from source rocks after studying the expelling rate of hydrocarbons from a unit volume of source rock. The third is to calculate the amount of oil and gas accumulation after studying the accumulation ratio coefficient of accumulated hydrocarbon to total expelled hydrocarbons. On this basis, the amount of oil and gas resources in place (GIP) was evaluated by multiply accumulated hydrocarbon amount with enrichment resource ratio coefficient, and the amount of recoverable oil and gas resources (TRR) was obtained by multiply the GIP with hydrate recovery factor. However, the current 35 evaluation results in the SCS were only the possible NGH amounts in GHSZ, which were calculated by multiply five parameters, including the area (A) and thickness (H), porosity (P), and hydrate saturation (Sgh) of GHSZ, and volume coefficient of hydrate at surface (E). These results were not in the category of resources in the strict sense, only be equivalent to the total possible amount of oil and gas calculated in the first step of conventional oil and gas resource evaluation study, the grade level is too low and the uncertainty is great, which cannot be used to guide NGH exploration. In order to have a more accurate NGH resources in the SCS, it is necessary to study the essential parameters, such as accumulation ratio coefficient, enrichment resources ratio coefficient, and recovery factor, and then make a more precise evaluation of the accumulated NGH amount, the GIP and the TRR.

Second, current results did not reflect the actual drilling results. For the evaluations conducted from 2001 to 2020, the average results of NGH resource almost remains unchanged, with a range between 60 and 90 $\times$ 10^{12} t of oil equivalent, which was inconsistent with the 1000 times reduction of the global NGH resource evaluation in the same period (Fig. 1), it was also inconsistent with the drilling results of the Shenhu Area in the SCS (Fig. 11). The NGH favorable area in Shenhu Area was predicted to be 3000 km^2, and the NGH resource potential was initially estimated based on BSR as 29 $\times$ 10^{12} m^3. In the next eight years, when the number of wells increased to five, the newly predicted favorable hydrate bearing area decreased to 425 km^2 and the resource decreased to 0.199 $\times$ 10^{12} m^3. In the following 10 years, the number of wells increased to 19 continually, and the favorable area further reduced to (22–600) km^2, with an average of 300 km^2, and the estimated NGH resource reduced to 0.066 $\times$ 10^{12} m^3. Compared with the first study, the area of the favorable area was reduced by 10 times, and the resource were reduced by three magnitude orders (Table 5).

Third, current resource evaluation results cannot be used to guide exploration. The results of the 35 evaluations are not the resource amount in the strict sense, but only the expected gas resource. Whether they can form the realistic NGH resources is also controlled by a series of geological conditions. Here are some examples when the expected gas resource cannot form NGH resource: (1) The areas with gas generation do not meet the conditions of NGH phase equilibrium; (2) Natural gas generated from the source rock cannot be discharged from the source rock; (3) Discharged natural gas cannot migrate into reservoirs with high porosity and permeability; (4) Accumulated NGH cannot be enriched as effective resources. Considering these uncertainties, it is difficult to apply these results to guide further exploration and development or to formulate development strategies.

4. Future development direction

4.1. Establishing objective criteria for identifying NGH resources

After determining the distribution of GHSZ, it is not enough to confirm the presence of NGH only by the BSR characteristics, as their accuracy and reliability are really low. The drilling results in the Shenhu Area of the SCS have proved that the BSR displaying areas in the GHSZ can also have no NGH resource, it is necessary to

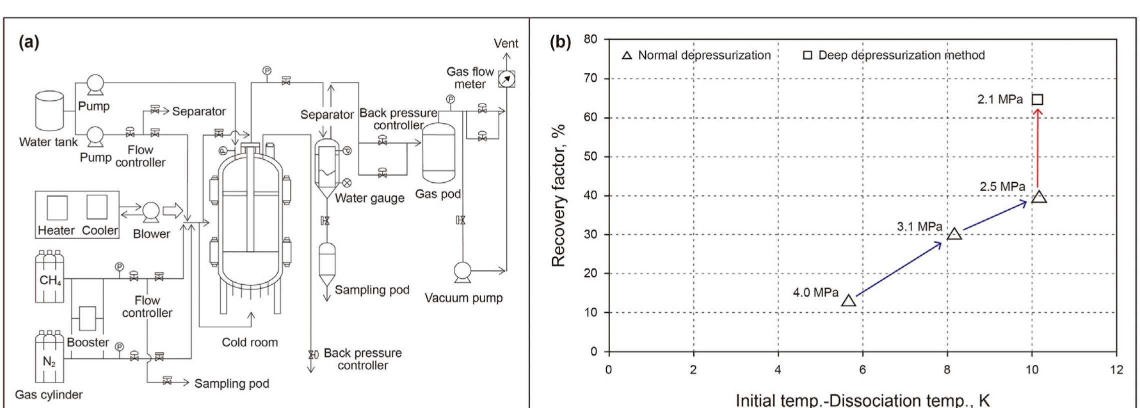

Fig. 10. Physical simulation experiment results of recovery factor (Konno et al., 2014). (a) Schematic diagram of experimental flow; (b) Physical simulation experiment result.

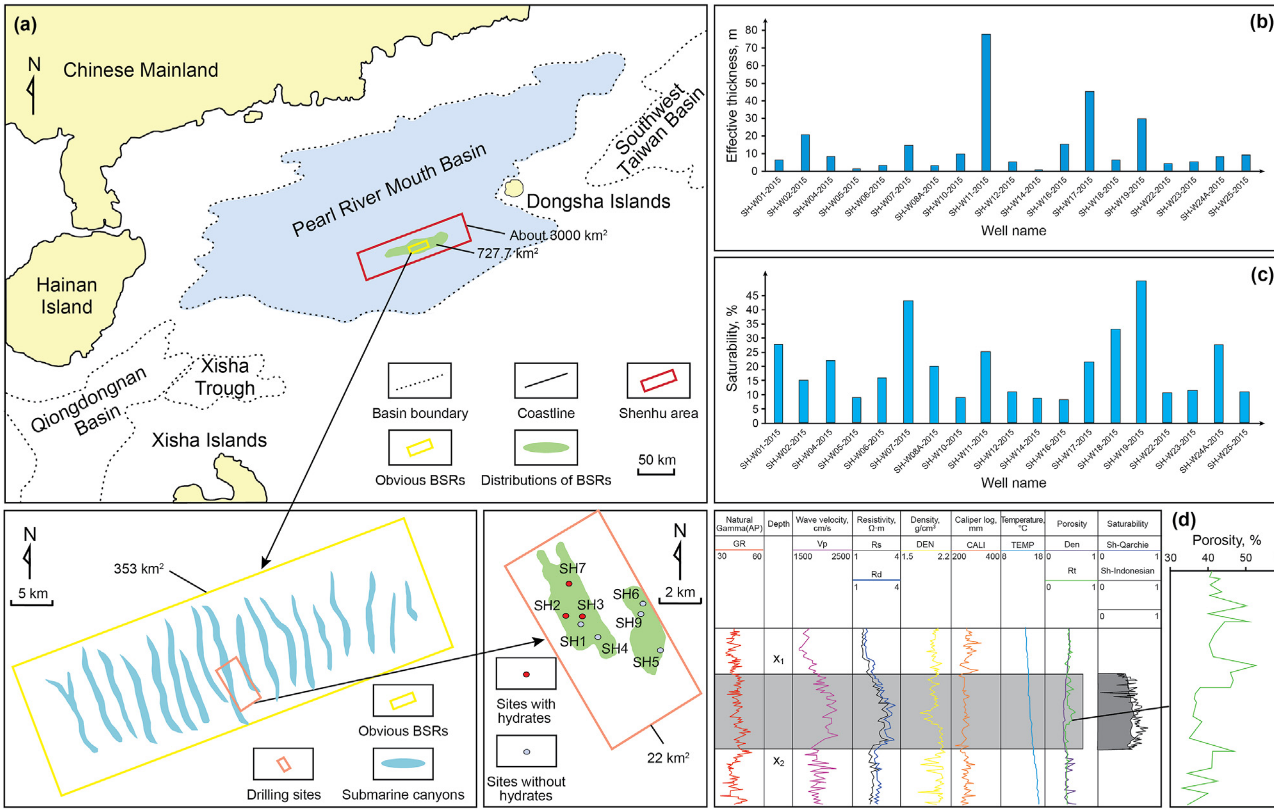

Fig. 11. Location and exploration results of gas hydrate reservoir in the Shenhu Area, Pearl River Mouth Basin, SCS. (Pang et al., 2021). (a) The location of Shenhu area and the prediction results of favorable area for NGH development, modified from Su et al., 2014; the Shenhu Area predicted by seismic data (red frame area 3000 km^2); the favorable production area determined after drilling 19 wells (22 km^2). (b) Effective thickness of NGH reservoir in 2015, data reference (Yang et al., 2017). (c) NGH saturation, data reference (Yang et al., 2017). (d) NGH porosity of W2 well in the Shenhu Area in 2007, data references (Wang et al., 2010b; Lu et al., 2008).

Table 5
Distribution parameters of the Shenhu gas hydrate reservoirs in China South Sea at different exploration stages and the resulting natural gas resource estimations.

Time	Condition	Area, km^2	Thickness, m	Porosity, %	Saturation, %	Gas volume conversion coefficient	In place gas volume, m^3
Before1999	Seismic data	3000	300	20	100	160	29×10^{12}
1999–2007	5 wells	425	25	45	25	164	0.199×10^{12}
2007–2017	19 wells	22–600	1–77.3	15–60	5–50	160	0.066×10^{12}
		300	14.18	35	28		

add other methods or parameters or technical means to intensify the identification.

4.2. Employ new theories and understandings in global NGH studies

Recently, the United States, Japan, South Korea, India and other countries have made new achievements in NGH exploration. A lot of papers have been published, which have deepen our understanding of NGH resource and its distribution characteristics. However, these new understanding have not been applied in the NGH evaluation in the SCS, the NGH researches in China is mainly focused on engineering and technology, and the resource evaluation in the SCE is falling behind the global NGH resource evaluation researches.

4.3. Investigate the correlation between NGH and conventional oil and gas

The selection of evaluation parameters in the SCS varies greatly and have many controversies. This is because the NGH studies are still very generalized and not specified to basins or areas. In the following studies, we need to consider the differences of each basin and make detailed analyses one by one to improve evaluation accuracy. In addition, the correlation between NGH resources and conventional oil and gas resources should be studied. The composite accumulation model of multi-sources, multi-dynamic and multi-phase oil and gas resources and the mass balance laws of multi-category resources should be built. Utilizing the accumulated knowledge and assessed resource amount of conventional oil and gas exploration to calibrate the NGH resource. By analyzing biogenic gas and thermal degraded gas as dual sources of the NGH to delineate the distribution range of effective source rocks to improve the accuracy of future evaluations.

4.4. Innovate theory and method for NGH resource evaluation in SCS

NGH is significant different from conventional oil and gas, tight oil and gas, and shale oil and gas. In the early exploration stage, we can utilize the unified volume method for resource evaluation. However, with exploration and researches deepen, the differences of these different types of resources will present various challenges in resource evaluation. At present, there are great uncertainties in the NGH evaluation in the SCS, mainly due to the lack of systematic and scientific theories and methods for resource evaluation. Therefore, the future NGH researches should focus on the innovation of resource evaluation theories, methods, and related technologies, such as the correlation of formation conditions and genetic mechanism of NGH and conventional oil and gas resources, and try to establish the symbiosis model and mass balance equation of multi-sources, multi dynamics and multi-phase natural gas resources and develop new technologies for NGH resource evaluation and improve the evaluation accuracy.

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