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Original Paper

Evaluation of natural gas hydrate resources in the South China Sea using a new genetic analogy method

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ABSTRACT

Natural gas hydrate (NGH) has attracted much attention as a new alternative energy globally. However, evaluations of global NGH resources in the past few decades have casted a decreasing trend, where the estimate as of today is less than one ten-thousandth of the estimate forty years ago. The NGH researches in China started relatively late, but achievements have been made in the South China Sea (SCS) in the past two decades. Thirty-five studies had been carried out to evaluate NGH resource, and results showed a flat trend, ranging from 60 to 90 billion tons of oil equivalent, which was 2–3 times of the evaluation results of technical recoverable oil and gas resources in the SCS. The big difference is that the previous 35 group of NGH resource evaluations for the SCS only refers to the prospective gas resource with low grade level and high uncertainty, which cannot be used to guide exploration or researches on development strategies. Based on the analogy with the genetic mechanism of conventional oil and gas resources, this study adopts the newly proposed genetic method and geological analogy method to evaluate the NGH resource. Results show that the conventional oil and gas resources are 346.29 × 10^8 t, the volume of NGH and free dynamic field are 25.19 × 10^4 km^3 and (2.05–2.48) × 10^6 km^3, and the total amount of in-situ NGH resources in the SCS is about (4.47–6.02) × 10^{12} m^3. It is considered that the resource of hydrate should not exceed that of conventional oil and gas, so it is 30 times lower than the previous estimate. This study provides a more reliable geological basis for further NGH exploration and development.

1. Introduction

Natural gas hydrate (NGH) is an ice-like crystalline compound formed in low temperature and high pressures, which is mainly composed of natural gas and hydrogen (Sloan and Koh, 2007). Recently, the oil and gas exploration and development shift from the conventional to the unconventional (Wang et al. 2020, 2021a, Wang et al., 2021c). Due to high energy density and low pollution to the environment, NGH are considered an ideal new resource after the shale oil revolution (Kerr, 2004; Cui et al., 2018; Hu et al., 2018; 2021a, 2021b). Researches on NGH have attracted much attention all over the world, especially in developed countries and countries lacking of conventional oil and gas resources (Zhang et al., 2021). At present, NGH researches are still at the early stage, such as the trial production. As of 2019, 19 voyages of NGH exploration have been carried out globally (Kerr, 2004), and NGH samples have been successfully extracted from northern Alaska, Japan Trough, and South China Sea (SCS) (Wang et al., 2017). These samples and preliminary data help scientists around the world to conduct more in-depth studies of NGH resources. NGH resource evaluation is essential as it provides scientific guidance to the actual exploration and reduces development risks. Meanwhile, studying the amount and distribution of hydrate resources is also helpful for countries to formulate appropriate energy policies. Global researches on NGH resource evaluation began in 1973, with two main evaluation methods, including volumetric method and particle organic carbon deposition rate method. The evaluation results up to date have

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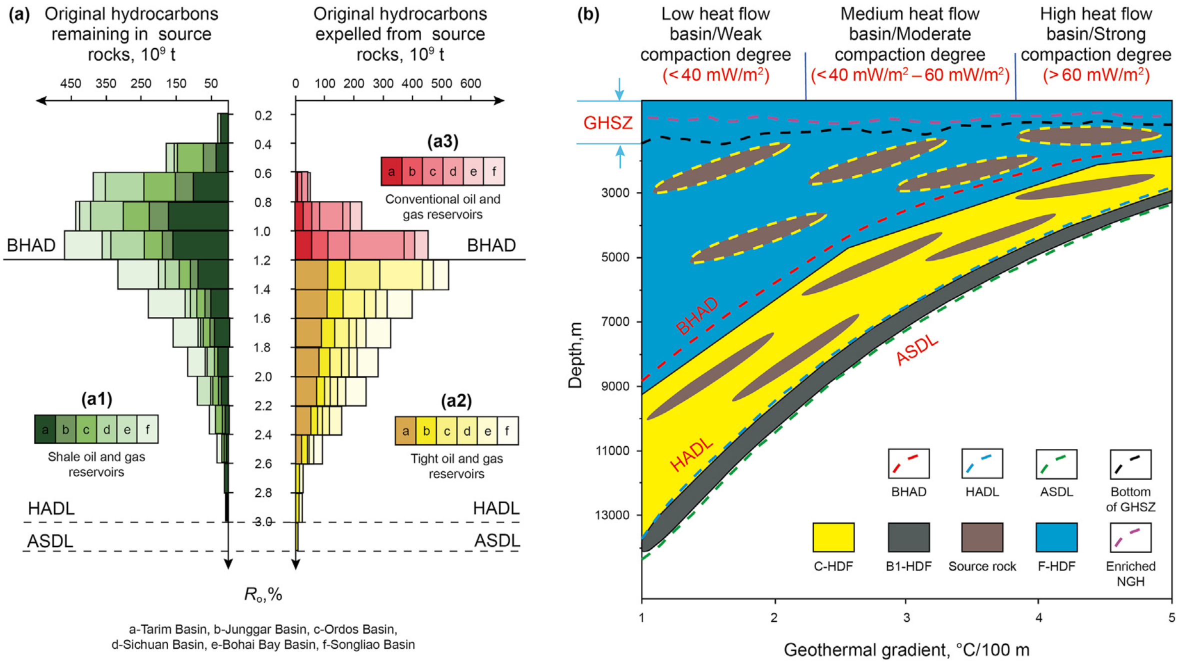

Fig. 1. Diagrams of hydrocarbon generation, retention and expulsion in vertical section and their relationship with hydrocarbon dynamic fields in petroliferous basins (Pang et al., 2021b). (a) Relationship among hydrocarbon generation, retention and expulsion of source rocks and the buoyancy-driven hydrocarbon accumulations depth in six representative basins of China; (b) The unified model of three dynamic boundaries and three dynamic fields controlling hydrocarbon accumulation. The blue area refers to F-HDF, controlling conventional oil and gas resources. The yellow zone refers to confined hydrocarbon dynamic field (C-HDF), controlling tight oil and gas resources. The gray area refers to bound hydrocarbon dynamic field (B1-HDF) controlling shale oil and gas resources.

decreased by 10,000 times since 1973 and are continuing to decline (Pang et al., 2021a; Pang et al., 2021c; Shaibu et al., 2021), indicating that with the improved understanding of hydrate, the NGH resource evaluation is gradually getting closer to the true value.

China started to evaluate NGH resources in the SCS since 2001, and by 2020, 35 estimates were obtained (Xu et al., 2021), which show three features. First, the estimates are all in the range of (60–90) × 10^{12} m^3 with no substantial change in the past 20 years, which is significantly different from the dramatic changes of the global NGH resource estimates. Second, the evaluation methods used in the SCS are mainly classical volumetric method and comprehensive analysis method, which are greatly affected by human factors. The volumetric method, utilized in 10 of the 35 evaluations, is based on the distribution characteristics of NGH resources (Xu et al., 2021), and the resource was obtained by multiplying parameters area, thickness, porosity, and hydrate saturation of NGH reservoirs, and volumetric coefficient of NGH at surface condition. This calculation is easy once all the geological parameter values are determined but the determination of these values can be very subjective and erroneous when the exploration level is low. The comprehensive analysis method, utilized in 23 of the 35 evaluations, is mainly based on the results obtained by volumetric method (Xu et al., 2021), where the original results are calibrated in the analysis with corrections and additional considerations, meaning more easily affected by human factors. The genetic method was used in only two studies, which evaluates the NGH resource according to hydrocarbon source. The advantage is that fewer parameters involved compared to the volumetric method, but the disadvantage is that it is hard to know exactly how much hydrate can be formed in the source rock and then accumulated into the reservoir. Besides, the genetic method does not take the contribution of deep degraded gas into account and ignores the mass balance relationship between NGH and other resources. Third, the 35 estimates are all relatively optimistic and is 2–3 times of the total recoverable NGH resources in the world (Boswell, 2009; Boswell and Collett, 2011). A detailed review of previous evaluations shows that, the 35 estimates of the NGH in SCS are only prospective gas resource, not the enriched or technical recoverable resource, so they cannot be used to guide NGH exploration and development or strategic researches in the SCS (Xu et al., 2021).

In order to overcome the shortcomings of the above methods and obtain more objective estimate of NGH resource in the SCS, this study reevaluated the in-situ NGH resources using a newly proposed genetic analogy method based on the mass balance law and the evaluated conventional oil and gas resources (Pang et al., 2021a).

2. Methods

NGH has always been considered to have an inorganic origin (Di et al., 2003). However, the carbon isotope content ($\delta^{13}C_1$) of methane in 13 global NGH reservoirs was found to be less than −30‰ (Pang et al., 2021a; Liang et al., 2021), indicating that all the NGH are from the degradation of organic matter in sedimentary basins. Biodegradation and deep thermal degradation provide 60% and 40% of the hydrates respectively, this is similar to the proportion of biogenic and thermal gas in oil and gas resources in petroliferous basins (Dai et al., 2017), indicating that NGH has the same source as other natural gas resource. This indicates that the total amount of NGH resources should not exceed the total amount of oil and gas resources generated by sedimentary organic matter (Fig. 1a). In addition, NGH is considered a special type of conventional oil and gas resource, accumulated in the sandstone reservoirs with high-porosity and high-permeability or the mudstone with fractures driven by buoyancy (Zhang et al., 2017). Therefore, the NGH resource amount is related to the amount of hydrocarbon amount expelled from source rocks above the buoyancy-driven

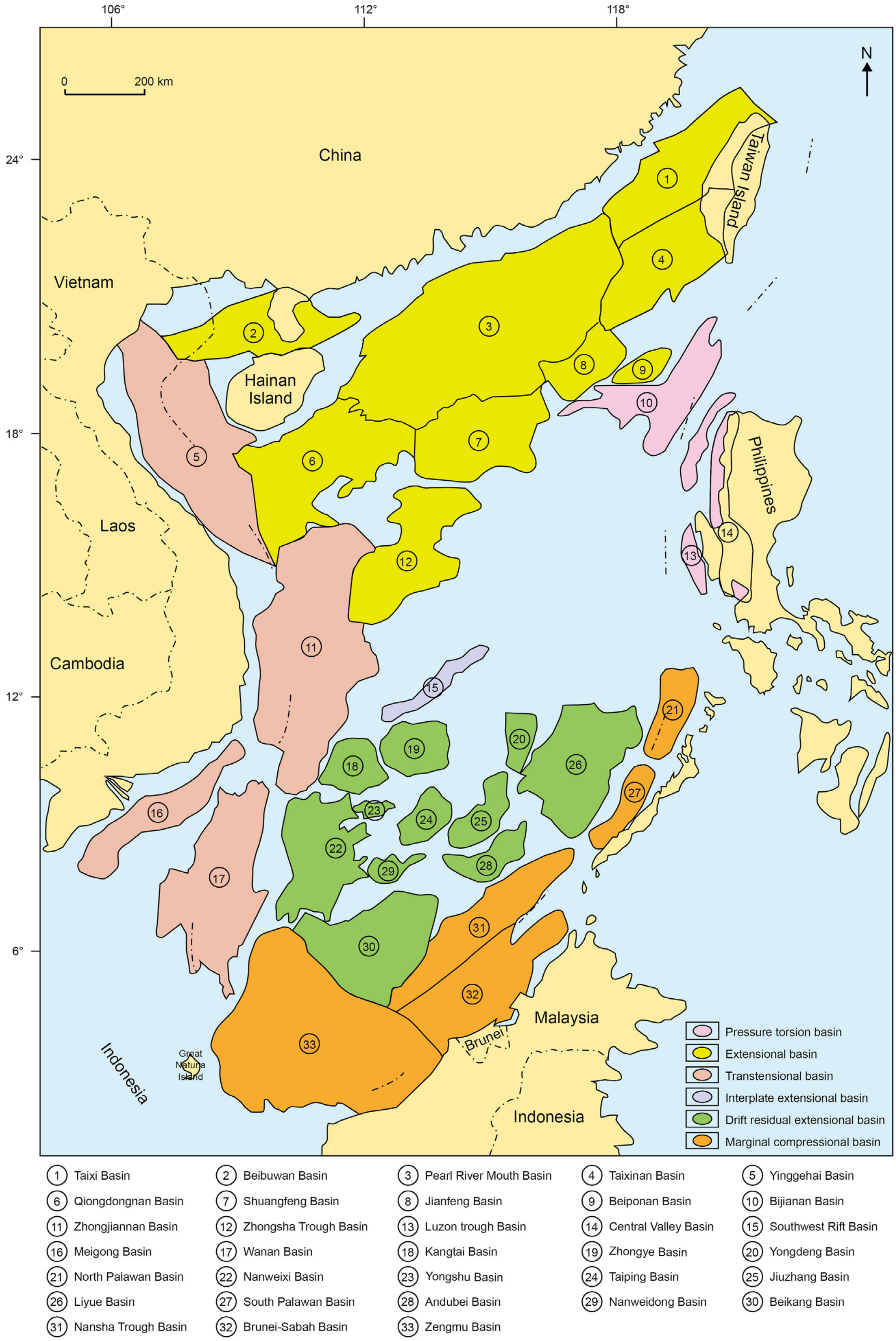

Fig. 2. Major basin distribution in the SCS (modified from Zhang et al., 2013).

Table 1
Sedimentary characteristics of main basins in South China Sea.

Basin	Area, km^2	Sedimentary thickness, m	Water depth, m	Sedimentary strata	References
Taixinan Basin	5.40	3548.84	50–3000	Late Cretaceous - Quaternary	Gong et al. (2012)
Pearl River Mouth Basin	26.70	3393.42	0–1500	Eocene -Quaternary	Mi et al. (2019)
Qiongdongnan Basin	3.40	4195.99	0–2000	Eocene -Quaternary	Zhang et al. (2015)
Zhongjiannan Basin	13.10	2139.07	50–4000	Eocene -Quaternary	Liu et al. (2020)
Wanan Basin	4.00	7110.78	500–2000	Late Eocene - Quaternary	Zhang et al. (2017)
Nanweixi Basin	4.80	2309.27	800–3600	Paleocene - Quaternary	Xu et al. (2003)
Zengmu Basin	16.87	7275.93	40–1800	Paleocene - Quaternary	Yao et al. (2008)
Beikang Basin	5.92	4612.73	100–1200	Paleocene - Quaternary	Lei et al. (2017)
Brunei Sabah Basin	9.40	6731.71	300–2200	Eocene -Quaternary	Liu et al. (2018)
Liyue Basin	5.50	2771.7	0–2000	Late Jurassic - Quaternary	Sun et al. (2010)
Palawan Basin	4.68	2779.87	1815.38*	Paleocene - Quaternary	Zhang et al. (2013)
Bijianan Basin	4.20	1589.52	1800–4400	Eocene -Quaternary	Gao and Bai (2002)
Shuangfeng Basin	3.70	1581.60	2000–3500	Eocene -Quaternary	Zhang et al. (2020)

Note: Sedimentation thickness is average, data Straume et al., (2019); * is the average value.

hydrocarbon accumulation depth (BHAD) (Pang et al., 2021b), and should be less than it (Fig. 1a). The BHAD boundary and related hydrocarbon dynamic field model were proposed by Pang et al. (2020a,b) (Fig. 1b). The formation area above the BHAD is the free hydrocarbon dynamic field (F-HDF), consisting of conventional oil and gas reservoirs, reformed heavy oil and bitumen reservoirs, and solid hydrates. In this field, the formation area dominated by buoyancy for hydrocarbon migration and accumulation (Pang et al., 2021b), therefore the NGH resource amount is also a part of the total amount of oil and gas resources in the F-HDF. According to the mass balance law, the NGH resource can be estimated through the genetic analogy method by multiplying the volume ratio of the gas hydrate stable zone (GHSZ) to F-HDF and conventional oil and gas resources (Pang et al., 2021b) (Equations (1) and (2)).

$$Q_{NGH} \approx R_{NGH} \times Q_{con} \tag{1}$$

$$R_{NGH} = \frac{V_{GHSZ}}{V_{FHDF}} = (A_{GHSZ} \times H_{GHSZ}) \Big/ (A_{FHDF} \times H_{FHDF}) \tag{2}$$

where, Q_{NGH} is the NGH resource amount, 10^{12} m^3. Q_{con} refers to the total amount of conventional oil and gas resources, 10^{12} m^3. R_{NGH} is the volume ratio of GHSZ in the F-HDF. V_{FHDF} is the rock volume of F-HDF, km^3. V_{GHSZ} is the rock volume of GHSZ, km^3. A_{GHSZ} is the area of GHSZ, km^2. H_{GHSZ} is the thickness of the GHSZ, m. A_{FHDF} is the area of the F-HDF, km^2. H_{FHDF} is the thickness of the F-HDF, m.

3. NGH resource evaluation in the SCS

The SCS, with an area of about 350 × 10^4 km^2, is one of the largest marginal sea basins in the Western Pacific Ocean. Located at the junction of the Pacific plate and Indian plate, it is a typical superimposed marginal sea basin. After a series of stretching and compression movements, the SCS formed passive continental margin and active continental margins with 38 large and medium-sized sedimentary basins (Fig. 2), with an area of about 106 × 10^4 km^2. There are 14 main sedimentary basins with an area of 74 × 10^4 km^2. These basins mainly developed at Paleogene to Quaternary strata, with thicknesses of 1581.6 m–7275.93 m and water depths of less than 4400 m (Table 1). These strata contain abundant sedimentary organic matter (Wu and Wang, 2018) and provide sufficient gas source for NGH formation (Yu et al., 2014; Li et al., 2021). Meanwhile, there are also many favorable geological conditions for gas migration, such as the accretionary wedge formed by the southward subduction of the ancient SCS and slump bodies and faults (Zhang et al., 2013; Cai et al., 2020). These geological bodies form a good transport system for NGH migration and accumulation (Qiao et al., 2013).

3.1. GHSZ distribution

GHSZ refers to an area where NGH can reach phase equilibrium and is confined by low temperature and high pressure that are conducive to the NGH formation and distribution (Booth et al., 1998). Wang et al. (2021) mapped the GHSZ in the SCS by studying the balance mode of gas hydrate phase in 12 major petroliferous basins in the SCS and correcting the sedimentary thickness with geothermal gradient (Fig. 3). The area of GHSZ in the SCS is 54.81 × 10^4 km^2, accounting for 51.71% of the total area of the sedimentary basins in the SCS and 18.27% of the entire area of the SCS. The thickness of GHSZ varies between 10 m and 800 m, with an average of 282.2 m. The rock volume in the GHSZ is 25.19 × 10^4 km^3, accounting for 4.56% of the total rock volume in the sedimentary basins.

3.2. Prediction of F-HDF for conventional oil and gas resource formation

Pang et al. (2020, 2021b) proposed the concepts of BHAD and hydrocarbon dynamic field. By combing lots of reservoir analyses and a series of physical simulation experiments, Pang et al. (2020a,b) found that the BHAD in petroliferous basins generally corresponds to a sandstone reservoir with porosity of 10% ± 2%, permeability of 1 mD, and pore throat radius of 1 μm. In this study, reservoir porosity and test data were used to determine the BHAD in Zhu-I Depression, Pearl River Mouth Basin. Fig. 4 shows the correlation between reservoir porosity and burial depth in Lufeng Sag, Zhu-I Depression, in which the porosity of 10 ± 2% corresponds to a depth of 3400–4000 m (Fig. 4b), therefore the BHAD in the Zhu-I Depression is determined as 3400–4000 m (Fig. 4a). Similarly, combined with the thickness map of sedimentary strata in the SCS (Straume et al., 2019), the thicknesses of the free dynamic fields in major basins were obtained, with an average of 2000–2700 m (Fig. 5). The volume of sedimentary strata in the F-HDF of the SCS is 2.05–2.48 × 10^6 km^3.

3.3. Conventional oil and gas resource evaluation

Combined with the national oil and gas resource evaluation results and previous studies on the resource evaluation of some basins in the SCS, conventional oil and gas resource amount in the

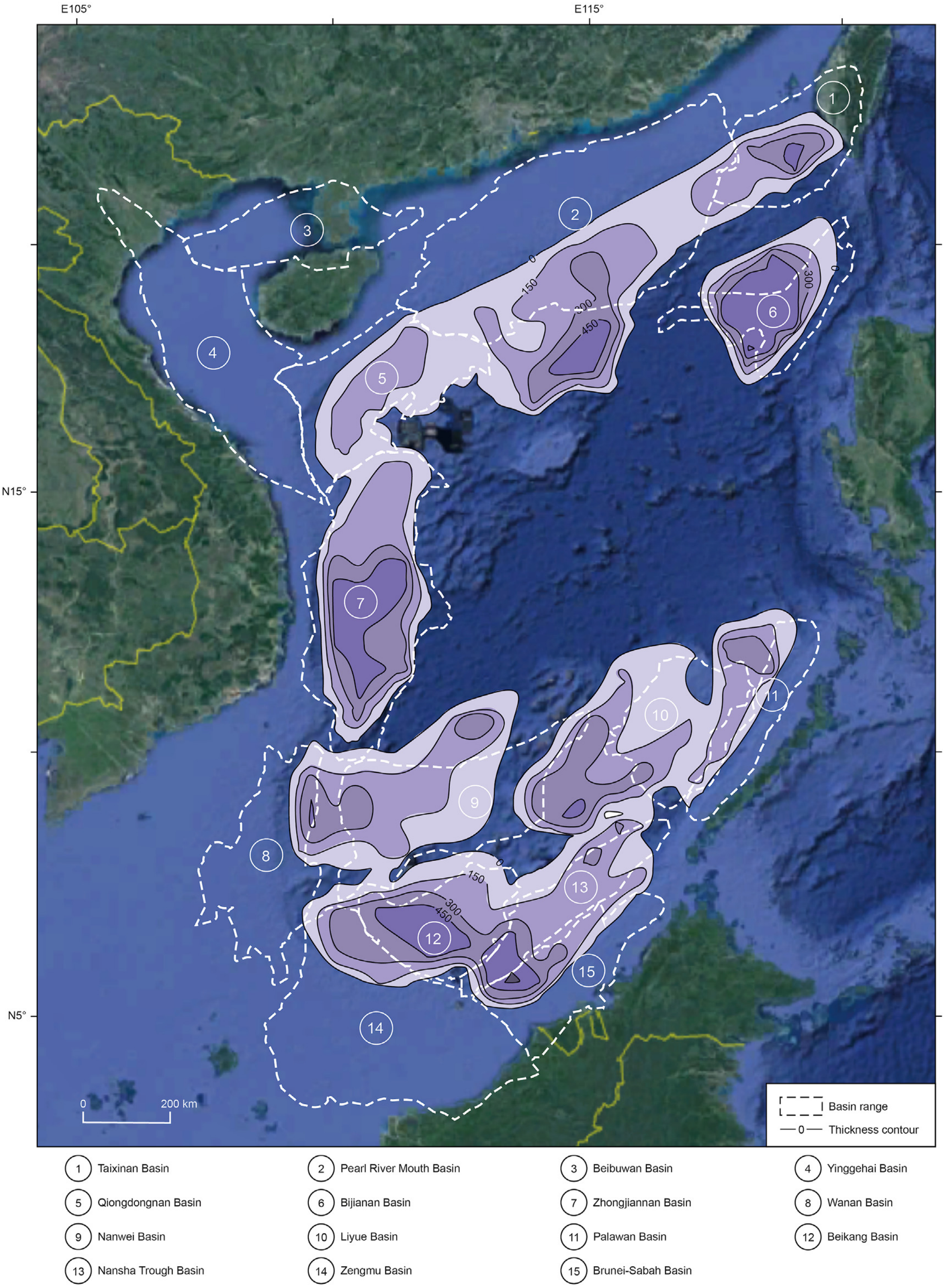

Fig. 3. Thickness distribution of GHSZ in SCS (modified from Wang et al., 2021b).

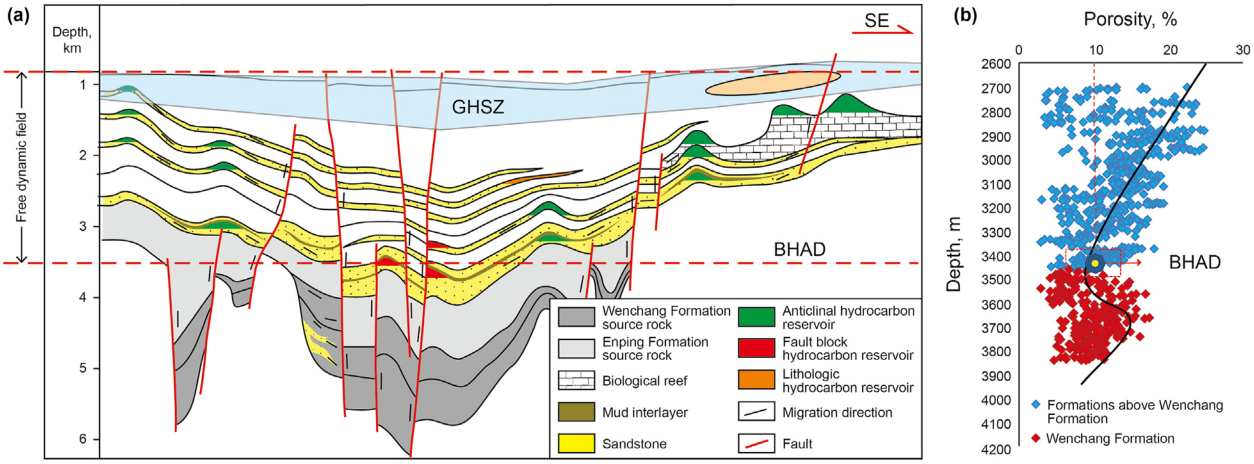

Fig. 4. F-HDF distribution in the SCS. (a) Distribution of the F-HDF and its relationship with the BHAD and distribution of conventional oil and gas resources in the Pearl River Mouth Basin; (b) Correlation between reservoir porosity and burial depth. The BHAD corresponds to the depth of 3400–4000 m.

SCS is 346.29 × 10^8 t, including conventional oil resource of 163.96 × 10^8 t and conventional natural gas resources of 182.33 × 10^{11} m^3 (Table 2) (Ministry of Land and Resources, 2009; Zuo et al., 2016; He et al., 2017; Zhang et al., 2017a, 2017b, 2017c; Zhu et al., 2019).

3.4. NGH resource evaluation

According to the thickness distribution of the F-HDF in basins and the GHSZ distribution map (Figs. 3 and 5), the flattening thickness, which refers to the flattening of an irregular polyhedron into a regular polyhedron of the same thickness for the convenience of calculation, was obtained by using isoline area tradeoff method, and then the V_{GHSZ} and $V_{F\text{-}HDF}$ were obtained by combining the area on the distribution maps. The volume ratios of GHSZ to F-HDF and the NGH resources (Q_{NGH}) in all basins were obtained by Equations (1) and (2) (Table 3). The average volumes of GHSZ and F-HDF in basins in the SCS are 1.80 × 10^4 km^3 and (1.57–1.91) × 10^5 km^3 respectively, and the total volumes are 2.35 × 10^5 km^3 and (2.05–2.48) × 10^6 km^3, respectively. The average R_{NGH} is 12.21%–16.34%. Applying this value to basins without GHSZ and F-HDF data, the NGH resources of all the basins are (4.47–6.02) × 10^{12} m^3 (Fig. 6). Pang et al. (2021a) found that R_{NGH} values are generally below 10% in 29 groups of global NGH resource evaluation results, whereas that of 7 basins in the SCS are greater than 10%, including Zhongjiannan Basin, Wanan Basin, Zengmu Basin, Beikang Basin, Nansha Trough Basin, Brunei Sabah Basin, and Bijianan Basin. This indicates that the SCS is favorable for NGH formation.

The estimate obtained in this study is 30 times smaller than that of the previous 35 studies, which might due to two reasons. First, the evaluation method utilized in this study is genetic analogy method. The NGH resource is considered as a part of the conventional oil and gas resources, so the NGH resource cannot exceed the total amount of the conventional oil and gas resources in the SCS. Second, the previous 35 evaluation results are all about prospective gas resource. However, the in-situ conventional oil and gas resource was utilized in this study and also considered the hydrocarbon expulsion, accumulation and enrichment in analogy, therefore this NGH resource estimate is in-situ resources, representing a higher grade level resource than the previous results.

4. Discussion

Based on the genetic analogy method, this study adopts the mass balance law and conventional oil and gas resource evaluation results to calculate the in-situ NGH resources in the SCS, which greatly improves the accuracy and credibility of the resource evaluation results. However, the estimate is also affected by two factors. First, the uncertainty mainly lies in the BHAD determination. As the BHAD in the Zhu-I Depression of the Pearl River Mouth Basin was used to represent the BHAD in the SCS, it might lead to some deviation due to individual differences among different basins. In the future, with more reservoirs data were obtained in basins, the BHADs in different basins should be independently determined to improve the accuracy of evaluation. Second, the conventional oil and gas resource evaluation in this study did not include the heavy oil and asphalt. By adding the heavy oil and asphalt resource, the estimated NGH resources should be larger than the current value. In addition, through physical simulation experiments and numerical simulations, the recoverable factor of NGH is 15%–70%, with an average of 30% (Boswell and Collett, 2011; Merey and Sinayuc, 2016). Based on these values, the technical recoverable resources of NGH in the SCS are (1.34–1.81) × 10^{12} m^3.

5. Conclusions

This study utilized a new genetic analogy method to evaluate the NGH resources in the SCS. (1) NGH is a special kind of conventional oil and gas resources in F-HDF in petroliferous basins, so the NGH resources in the SCS cannot exceed the total amount of conventional oil and gas resources. (2) The NGH resource in FHDF is directly proportional to the ratio of rock volume occupied by GHSZ and FHDF, which is less than 10% on average globally and between 12% and 16% in SCS. (3) According to the analogy method and the mass balance law, the in situ NGH resources in SCS are

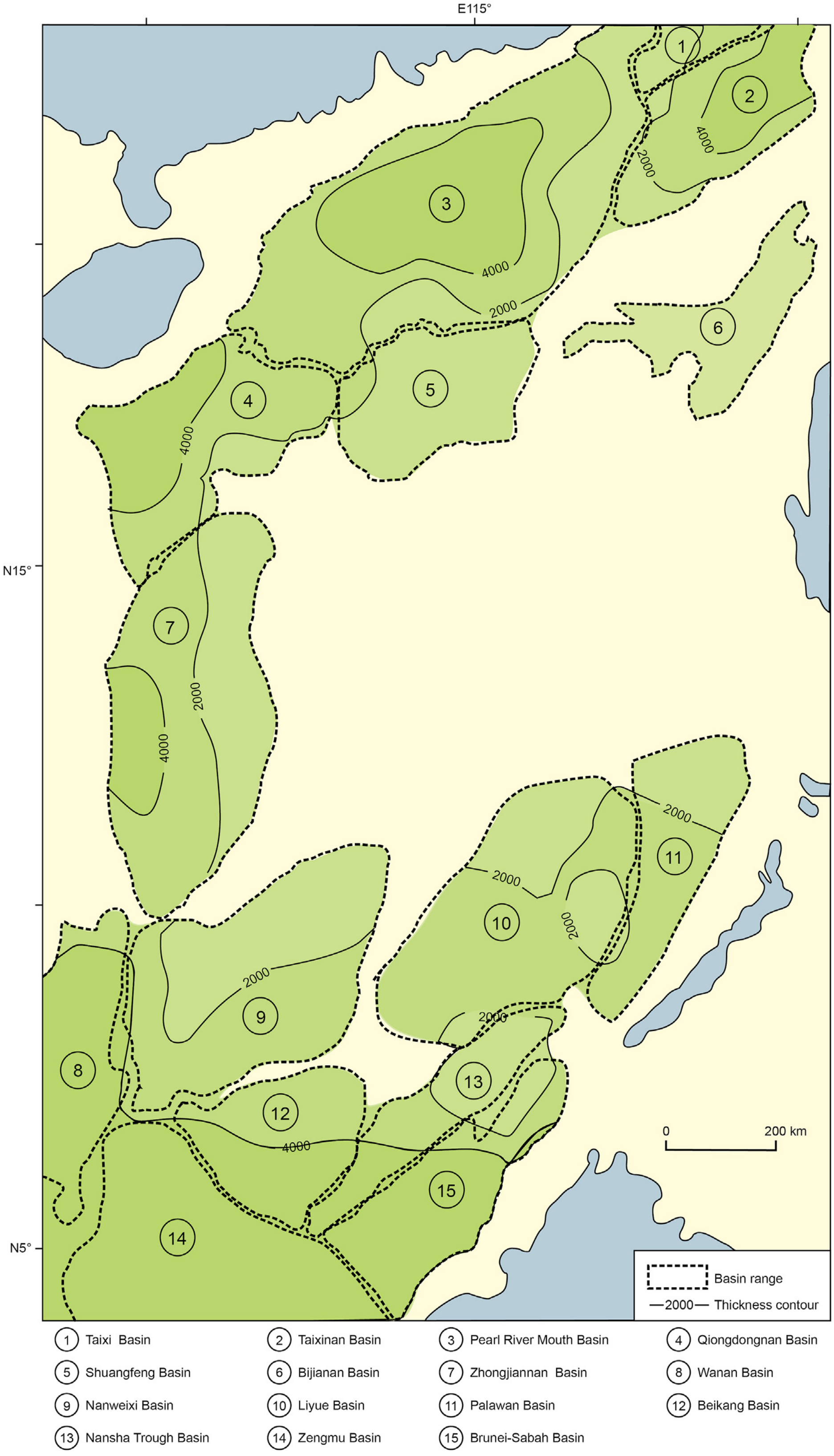

Fig. 5. Prediction of the free dynamic field distribution for major basins in the SCS.

Table 2
Comprehensive evaluation results of conventional oil and gas resources in major petroliferous basins in the South China Sea.

Basins	Thickness of F-HDF, m	Area of F-HDF, 10^4 km^2	Oil resources, 10^8 t	Gas resources, 10^8 m^3	Oil and gas resources, 10^8 t
Qiongdongnan Basin	1270–1690	10.87	2.72	11142.31	13.86
Yinggehai Basin	/	/	/	13067.98	13.07
Beibuwan Basin	/	/	7.34	/	7.34
Pearl River Mouth Basin	1267–1682	23.94	21.95	27,000	48.95
Taixinan Basin	1137–1743	7.67	1.85	2052.39	3.90
Liyue Basin	2011–2176	15.21	5.24	3427.01	8.66
Zengmu Basin	3400–4000	13.19	33.51	43130.61	76.64
Brunei Sabah Basin	636–719	7.73	21.63	3982.59	25.61
Nanweixi Basin	2145–2309	15.44	8.43	13,382	21.81
Beikang Basin	656–1871	6.73	13.82	14,855	28.68
Zhongjiannan Basin	2066–2139	17.62	19.06	7233.65	26.29
Wanan Basin	359–400	5.57	16.31	34.90	51.21
Palawan Basin	1832–2780	7.19	4.42	4073.99	8.49
Bijianan Basin	1590	9.78	4.17	2364.96	6.53
Other basins	/	/	3.51	1720.86	5.23
Total	/	146.19	163.96	182330.35	346.29

Note: "/" is no data.

Table 3
Key parameters and evaluation results of NGH resources in the SCS.

Basins	V_{GHSZ}, 10^4 km^3	$V_{F\text{-}HDF}$, 10^4 km^3	R_{NGH}, %	Q_{CON}, 10^8 t	Q_{NGH}, 10^{12} m^3
Taixinan Basin	1.12	8.72–13.37	8–13	3.90	0.03–0.05
Peral River Mouth Basin	1.81	30.32–40.26	4–6	48.95	0.22–0.29
Qiongdongnan Basin	0.93	13.79–18.33	5–7	13.86	0.07–0.09
Zhongjiannan Basin	4.15	36.41–37.69	11	26.29	0.29–0.30
Wanan Basni	0.25	2.00–2.23	11–12	51.21	0.57–0.64
Nanweixi Basin	2.17	33.12–35.65	6–7	21.81	0.13–0.14
Zengmu Basin	0.91	4.48–5.27	17–20	76.64	1.33–1.56
Beikang Basin	2.11	4.42–12.59	17–48	28.68	0.48–1.37
Brunei Sabah Basin	1.68	4.91–5.55	30–34	25.61	0.78–0.88
Liyue Basin	3.10	30.57–33.09	9–10	8.66	0.08–0.09
Palawan Basin	1.21	13.17–19.98	6–9	8.49	0.05–0.08
Bijianan Basin	2.85	15.54	18	6.53	0.12
Other basins	/	/	12–16	25.64	0.31–0.41
Average	1.80	15.73–19.05	12–16	/	/
Total	23.46	204.60–247.71	/	346.27	4.47–6.02

Note: "/" is no data.

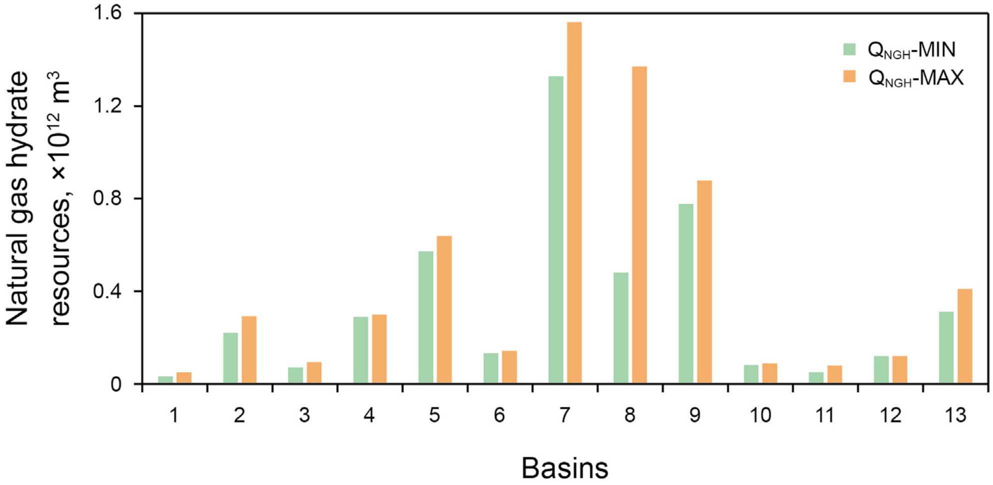

Fig. 6. Evaluation results of NGH in place resources in main basins of the SCS. 1-Taixinan Basin; 2-Pearl River Mouth Basin, 3-Qiongdongnan Basin, 4-Zhongjiannan Basin, 5-Wanan Basin, 6-Nanweixi Basin, 7-Zengmu Basin, 8-Beikang Basin, 9-Brunei Sabah Basin, 10-Liyue Basin, 11-Palawan Basin, 12-Bijianan Basin, 13-Other basins.

$(4.47–6.02) \times 10^{12}$ m^3, with total recoverable resources of $(1.34–1.81) \times 10^{12}$ m^3.

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