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Original article

Evaluation of CO_2 hydrate storage potential in the Qiongdongnan Basin via combining the phase equilibrium mechanism and the volumetric method

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Abstract:
Carbon dioxide capture, utilization and storage technology is considered to be one of the most effective strategies to mitigate CO_2 emissions. In this process, CO_2 that is injected into seabed sediments under specific temperature and pressure conditions is sealed in the form of CO_2 hydrate, known for its high gas storage density and exceptional security features. This method has significant advantages compared with onshore geological storage schemes. Thus far, however, there has been no industrial demonstration of CO_2 hydrate storage, and the CO_2 hydrate storage potential in the South China Sea remains underexplored without targeted evaluations. In this study, the phase equilibrium mechanism is combined with the volumetric method to describe and evaluate the CO_2 hydrate storage distribution range, effective thickness, and potential volume available for CO_2 hydrate storage. Based on the latest exploration and development data from the Qiongdongnan Basin, along with geological structure data, multibeam bathymetry, local high-resolution three-dimension multichannel seismic reflection data, logging data, and submarine heat flow data, the distribution of the CO_2 hydrate storage stability zone is determined. The results show that the effective thickness and regional scope of CO_2 hydrate storage in the concerned area can be determined by virtue of the local water depths and the submarine temperature and pressure of 18 virtual wells. The minimum water depth in the Qiongdongnan Basin that satisfies the temperature and pressure conditions needed for CO_2 sediment storage is established as 415 m. The theoretical geological storage capacity of CO_2 hydrate in the Qiongdongnan Basin is determined as 5.75×10^{11} to 8.73×10^{11} t, where the value range of E is between 0.56 and 0.85. These findings offer a solid foundation for China to create, advance and execute a viable strategy for CO_2 hydrate storage.

1. Introduction

Greenhouse gas emissions, particularly those of carbon dioxide (CO_2), have had a progressive negative impact on the global ecological environment. China's carbon emissions have increased by 25% in the past 10 years; in 2019, the total carbon emissions reached a carbon equivalent of 14.093 billion tons, accounting for 27% of the global total emissions (IEA, 2021). Approximately 90% of China's overall greenhouse gas emissions originate from the energy industry, encompassing both fossil fuel combustion and industrial activities, of which around 70% of energy-related emissions stem from coal, 12% from oil, and 6% from natural gas, while this proportion in other parts of the world accounts for only 60% (IEA, 2021; Ranaee et al., 2022). Research indicates

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that CO_2 concentration can be retained in the atmosphere for hundreds of years. China's fossil energy structure of "oil shortage, gas shortage and coal enrichment" (Ding, 2021; Xu et al., 2022) states that, to achieve long-term and efficient emission reduction targets, carbon capture, utilization and storage (CCUS)/carbon capture and storage technology must play a role in the process of carbon neutralization (Cuéllar-Franca and Azapagic, 2015). This technology is regarded as crucial in significantly lowering CO_2 emissions and is a technical necessity for achieving the "double carbon" goal (Wei et al., 2021; Xu et al., 2023).

Marine CCUS has been considered to have great storage potential (Dahowski et al., 2009). Marine CO_2 storage technology was first formally proposed in 1977 (Marchetti, 1977). After more than four decades of exploration and development, offshore carbon storage projects have been successfully implemented worldwide. The feasibility of offshore carbon storage has been fully verified, for example, in Salah in Algeria; the Sleipner and Snøhvit fields in Norway; the Century Plant in the United States; Quest and Equistore in Canada; and the Pearl River Mouth Basin in China (Chadwick et al., 2004; Brydie et al., 2014; Ajayi et al., 2019). However, most of the above offshore carbon storage projects focus on the seabed sandstone reservoir (CO_2 saline aquifer storage), and the current progress made in the study of variable and suitable geological structures, related processes and capabilities is insufficient, which includes strategies such as injecting CO_2 into deep and shallow sediments for permanent storage in the form of CO_2 hydrate or utilizing CO_2 to produce additional methane hydrate (Verdon et al., 2013; Goudarzi et al., 2019; Ringrose and Meckel, 2019).

Over the last 20 years, China has carried out six hydrate drillings and two rounds of pilot production in the Qiongdongnan Basin (QDNB), and many in-depth studies have been conducted on these projects (Cai et al., 2020). The estimated value of the prospective resources of natural gas hydrate in the South China Sea is between 6 trillion cubic metres and approximately 87 trillion cubic metres, signifying their vast resource potential. One of the ways to recover methane from gas hydrate is through CO_2, that is, replacing CH_4 with CO_2. This achieves the formation of CO_2 hydrate stored it seabed sediments. Numerous scholars have argued for the feasibility of CO_2 hydrate storage from various perspectives (Guo and Zhang, 2023). Although the capacity of natural gas hydrate reserves may be huge, the assessment of the potential geological storage capacity of CO_2 hydrate in China's marine strata has not been carried out in detail. Several studies have evaluated the CO_2 storage potential of China's marine areas. For example, Zhang et al. (2010) and Li et al. (2023) evaluated the suitability and capacity potential of CO_2 storage in China's main sedimentary basins. Zhou et al. (2013) used the Carbon Storage Leadership Forum methodology for calculating the effective storage capacity of CO_2 in saline aquifers and oil and gas reservoirs. Li et al. (2021) evaluated the storage potential of CO_2-enhanced oil recovery in several offshore oil and gas fields. Wei et al. (2023) provided a comprehensive summary of the procedures for storage potential evaluation, and the workflows for calculating CO_2 storage capacity have been suggested. The above studies provide insights into the evaluation of the potential for CO_2 hydrate storage by the assessment of carbon dioxide storage potential in marine areas.

The present study uses the QDNB in the South China Sea as a case study and considers the form of CO_2 hydrate storage. Additionally, by considering the regional structure and reservoir characteristics along with parameters such as water depth, seabed temperature and the pressure of 18 virtual wells, the phase equilibrium curve of CO_2 hydrate is established to define the stable zone of CO_2 hydrate storage. The phase equilibrium mechanism and the volumetric method are combined to describe the distribution range and effective thickness of CO_2 hydrate storage, and the method of evaluating CO_2 hydrate storage potential is established. The results can not only offer a more dependable resource basis in China to devise strategies for the implementation and advancement of CO_2 hydrate storage but also serve as a reference for site selection in the further expansion of offshore CO_2 hydrate storage within China's maritime basins.

2. Regional geological setting

The QDNB is situated along the northern continental margin of the South China Sea, bordering the Yinggehai Basin in the west, the Hainan Island Uplift in the north, the Pearl River Mouth Basin in the northeast, and the Yongle Uplift in the south. Its overall direction is northeast-southwest, with an area of 8.92×10^4 km^2 (Fig. 1(a), according to Zhu et al. (2007)). The basin consists of five secondary structural units, namely, northern depression, central uplift, central depression, southern uplift, and southern depression (Fig. 1(b)). The secondary structural units of the basin include Songnan low uplift, Songnan-Baodao sag, Changchang sag, Beijiao uplift, Ledong sag, Lingshui sag, Lingnan low uplift, Beijiao sag etc. The basin began to extend the fault depression over the pre-Cenozoic basement and during the Cenozoic. Furthermore, the QDNB experienced a rifting period from the Eocene to the early Miocene (Ren et al., 2024), and a post-rifting period from the late Miocene to the present (T6 to the resent). The post-rifting period can be divided into thermal subsidence stage and accelerated subsidence stage (Clift and Sun, 2006; Liu et al., 2023), during which Palaeogene, Neogene and Quaternary units were deposited (Fig. 1(c), according to Lyu et al. (2021) and He et al. (2022)). Taking the fracture unconformity T6 as the boundary, the basin has a typical double-layer structure. Due to the special tectonic location (Zhou et al., 1995), the formation and evolution of the QDNB has been considered to be associated with the expansion of the South China Sea, subduction of the Pacific plate, and the Honghe fault. It is one of the key regions for studying the numerous tectonic events. Therefore, this study takes the QDNB as a typical example of a basin. The Ledong Formation has been deposited since the Quaternary and is mainly composed of deep-sea fine-grained argillaceous sediments; in this study, it is the main prospective target for CO_2 hydrate storage. The sedimentary facies vary from massive units of transported sediment to turbidites to semipelagic sediment (Fig. 1(c), according to Lyu et al. (2021). For a comprehensive study on the potential of

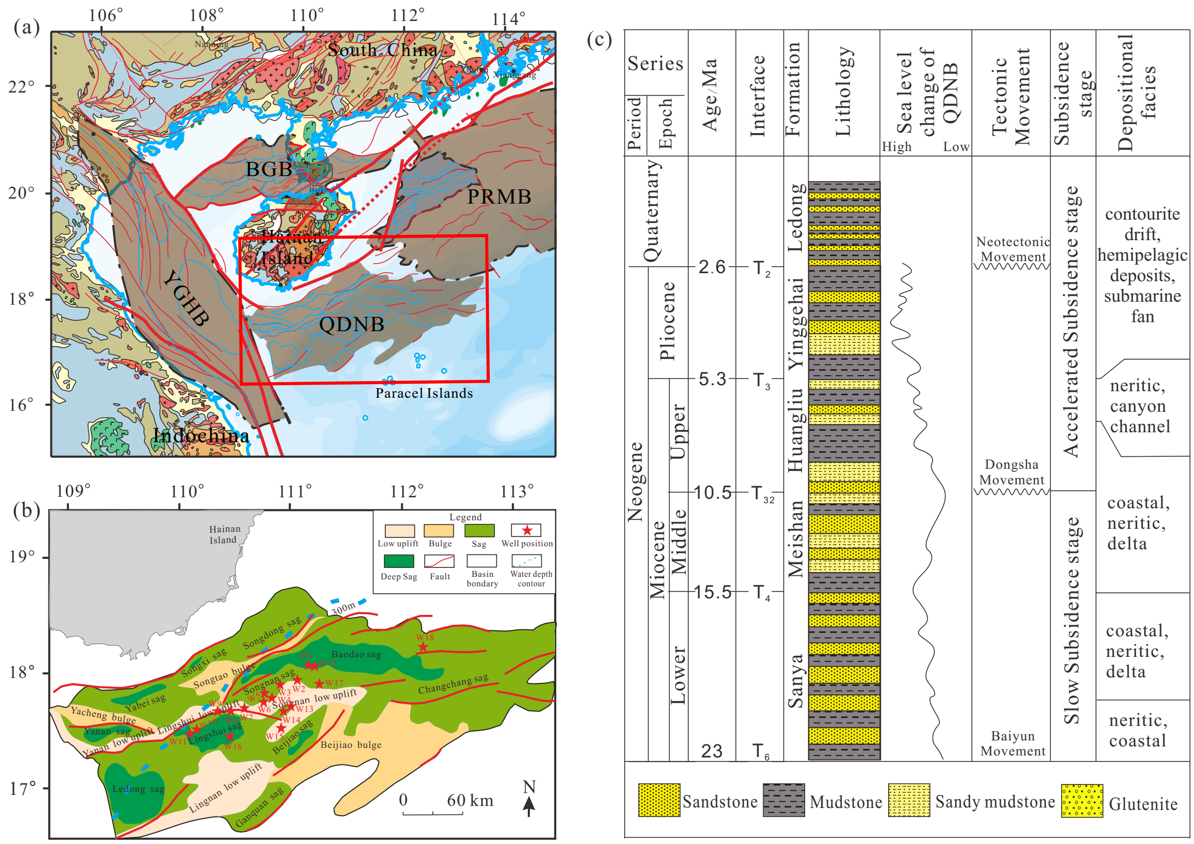

Fig. 1. (a) Location of the Qiongdongnan Basin in the northwestern South China Sea (red rectangle), (b) the study well locations in the QDNB and (c) stratigraphic column of the QDNB (compiled after Zhu et al. (2007) and Lyu et al. (2021)).

CO_2 hydrate storage in study area, 18 virtual wells were set in five secondary structural units (Fig. 1(b)).

3. Data and methods

3.1 Data

The data used in this paper includes regional geological structure data, multibeam bathymetry, local high-resolution 3D multichannel seismic reflection data, logging data, and submarine heat flow data from southeastern Hainan. The geothermal data, as well as the temperature measurement data for the 18 virtual wells, including wellhead temperature and pressure, corresponding water depth and geothermal gradient, were sourced from the Global Heat Flow Database (GHFD), available at http://www.ihfc-iugg.org/products/global-heat-flow-database (Table 1).

3.2 CO_2 hydrate storage mechanism

With increasing seawater depth, the temperature generally decreases and CO_2 exists in the shallow seawater in gas form. Furthermore, the pressure also rises, CO_2 gradually turns into liquid form, and its density increases. When a certain depth is reached, the CO_2 density will be greater than that of seawater. In the seabed sediment, however, the density of CO_2 decreases with depth; therefore, below a certain depth in the sediment, the density of CO_2 will decrease to below that of seawater. The area from this depth to the seabed is called negative buoyancy zone, which can be utilized for storing CO_2. When CO_2 is injected below this zone, as its density is less than that of seawater, and it will float up and stay at the bottom of the negative buoyancy zone. The sedimentary layer on the seabed typically exists under conditions of high pressure and low temperature. In the seabed, the temperature and pressure both increase with depth. Within a certain depth range, when the temperature and pressure conditions reach the CO_2 hydrate equilibrium conditions, the CO_2 hydrate will wrap the CO_2 molecules in water molecular bonds to form carbon dioxide hydrate and achieve storage. This region is referred to as the hydrate formation zone. The density of CO_2 hydrate was reported to range from 1,050 to 1,200 kg/m³, according to the prevailing temperature and pressure conditions. In other words, the thickness of the HFZ depends on temperature and pressure. Therefore, CO_2 injected into the sedimentary layer will slowly move up to the bottom of the HFZ to form hydrates under the effect of buoyancy and play the role of an effective capping layer, preventing more CO_2 from continuing to migrate upwards and forcing it to flow laterally. In this way, the hydrate layer will gradually expand. When the time scale is large enough and gravity and buoyancy are balanced, CO_2 will no longer migrate but will become stable and sealed in

Table 1. Key parameters of virtual wells.

No.	Well	Depth of water (m)	Geothermal gradient (°C/100 m)
1	11	1,447.2	44.3
2	12	1,547.1	37.2
3	13	1,530.5	47.9
4	14	1,446.4	46.1
5	15	1,252	47.8
6	16	1,365	42
7	17	1,688.7	52.9
8	18	1,714.2	45.9
9	19	975.4	43
10	20	959.7	45
11	21	1,041	46
12	QDN-W-01	1,851.5	65
13	QDN-W-07	1,422	103
14	QDN-W-08	1,378.5	102
15	QDN-W-09	1,361	113
16	5	1,335.8	44
17	18	1,908	47
18	19	2,154	63

the seabed sedimentary layer (House et al., 2006). Thus, injecting CO_2 below the hydrate stability zone can effectively store CO_2 and achieve CO_2 hydrate storage (Zhang et al., 2022).

3.3 Selection of evaluation methods for CO_2 storage capacity

The storage capacity of a geological formation denotes the quantity of CO_2 it can accommodate. To date, various institutions, organizations and scholars have proposed different methods for assessing the CO_2 storage capacity according to different storage mechanisms (Bachu, 2002). Existing studies conclude that geological parameters are key factors in evaluating the CO_2 storage capacity. The approaches utilized in most of these studies are founded on the methodologies of the Carbon Storage Leadership Forum or the United States Department of Energy method, as outlined by Goodman et al. (2013). The EIPED&CUP method is intended to improve foreign empirical formulas and has been widely used in China (Wei et al., 2013). Considering that most oil reservoirs in China are high water-cut reservoirs in which the mechanism of dissolution capture cannot be ignored, the EIPED&CUP method has developed a modified calculation method based on the Carbon Storage Leadership Forum. This method takes into account the issues of water injection and extraction, as well as the dissolution of CO_2. According to the current classification method, four types of CO_2 storage capacity are defined, in the ascending order of accuracy: theoretical capacity, effective capacity, practical capacity, and matching capacity (Bradshaw et al., 2007), where theoretical capacity indicates the maximum upper storage potential limit. Due to the special requirements of CO_2 hydrate storage, wherein the storage stability region is controlled by temperature and pressure, the current mainstream storage capacity calculation method has difficulty in meeting the evaluation requirements. Therefore, this work combines the phase equilibrium mechanism and the volumetric method to evaluate the theoretical geological storage capacity of CO_2 hydrate in deep-sea sediments.

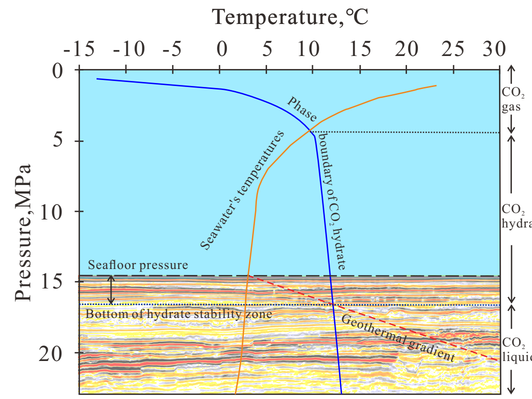

Fig. 2. Overview of the phase equilibrium of CO_2 hydrate. The red dashed line indicates the temperature of seawater and shallow sediment, the blue solid line depicts the phase boundary of CO_2 hydrate, while the orange solid line indicates seawater temperature.

3.4 Evaluation of CO_2 hydrate storage capacity by the phase equilibrium mechanism and the volumetric method

As outlined above, the physical state of CO_2 varies depending on temperature and pressure. In Fig. 2, the solid blue line represents the CO_2 phase boundary. At different ocean temperatures and depths, CO_2 can exist in gas phase, water phase or hydrate phase. The seawater temperature in southeast Hainan was obtained from the GHFD (available at http://www.ihfc-iugg.org/products/global-heat-flow-databas). In addition, the temperatures at some stations in southeast Hainan were also measured during the Guangzhou Marine Geological Survey drilling survey.

According to the phase equilibrium curve, the formation of CO_2 hydrates can only occur under high pressure and low temperature; therefore, it is necessary to evaluate the reservoir temperature and pressure. First, to accurately obtain the reservoir temperature, the seabed temperature must be determined (Wang et al., 2022):

$$T_0 = -8.7946 \ln Z + 62.958 \quad 100\ \text{m} < Z < 600\ \text{m} \tag{1}$$

$$T_0 = e^{(650667 - 0.735218 \ln Z)} \quad 600\ \text{m} < Z < 2,800\ \text{m} \tag{2}$$

where T_0 denotes the seabed temperature, °C; and Z denotes the depth of seawater, m.

Second, we calculate the change in seabed formation temperature:

Table 2. Corresponding CO_2 hydrate equilibrium pressures under different temperature conditions.

Temperature (K)	Pressure (kPa)
260	709.00
270	1,014.30
272	1,086.49
273	1,124.13
275	1,553.92
280	2,787.21
283	4,194.40
283.17	4,305.62
283.5	4,537.11
283.6	4,850.52
283.7	5,431.00
283.8	6,017.98
284	7,306.86
285	14,360.76
286	22,403.76
290	62,958.45
300	20,9625.80

$$T = T_0 + \frac{GZ}{100} \tag{3}$$

where T denotes the formation temperature, °C; G denotes the ground temperature gradient, °C/100 m.

Because the difference in gas composition will affect the temperature and pressure of hydrate formation, after determining the gas composition, the gas composition information was put into the Colorado School of Mines Hydrate program to obtain the CO_2 phase equilibrium boundary (blue) curve shown in Fig. 2. The seabed pressure can be calculated as:

$$P = \rho g h \tag{4}$$

where ρ represents the water density, 1.03 $\mathrm{g/cm^3}$; h represents the sea depth, m; g signifies the acceleration due to gravity, (10 m/s); and P is the pressure at the corresponding depth.

Depth is characterized by pressure, and the relationship between temperature and pressure is obtained as follows:

$$T = T_0 + \frac{GP}{100\rho g} \tag{5}$$

The bottom boundary pressure of CO_2 hydrate at the station is determined by finding the intersection point between the phase equilibrium curve of CO_2 hydrate storage and the temperature and pressure change curve at the corresponding station (the pressure control hydrate threshold curve shown in Fig. 2). According to the water depth of the station, the seabed pressure is obtained. Taking the difference between the two pressures as a basis, the CO_2 hydrate storage thickness at the station under temperature and pressure conditions is calculated.

This study uses the volumetric method to evaluate the CO_2 hydrate storage potential, based on principles introduced by Wang et al. (2022). The storage capacity can be obtained by:

$$N_{CO_2} = A \times H_{CO_2} \times \varphi \times \rho \times E \tag{6}$$

where N_{CO_2} denotes the theoretical storage capacity of CO_2 in the seabed sediment layer, m^3; A denotes the hydrate storage area, m^2; H_{CO_2} denotes the thickness of the CO_2 hydrate thickness under ambient temperature and pressure conditions, m; φ denotes the porosity of the sediment reservoir, %; ρ denotes the CO_2 density under formation conditions, $\mathrm{kg/m^3}$; and E denotes the conversion coefficient.

4. Results

The QDNB has suitable geological conditions for CO_2 hydrate storage; the basin exhibits the characteristics of both passive and active continental margins. Regarding the sedimentary conditions, the three phases of rapid sedimentation in the South China Sea have yielded numerous suitable locations for CO_2 hydrate storage. For example, based on the latest geological exploration data of the deep-water areas of the QDNB, a large channelized submarine fan developed in the shallow Ledong Formation, with longitude and latitude of 110 °E-112 °E and 17 °N-18 °N, respectively (Liu et al., 2023). The average porosity and permeability of the Ledong submarine fan samples are 40.5% and 312.2 mD, respectively. The Ledong Formation was less influenced by diagenesis and compaction due to its shallower burial depth, subsequently creating well-structured pore reservoirs. Therefore, the reservoir properties in the shallow Ledong Formation are favorable and conducive to CO_2 hydrate storage.

In order to obtain the theoretical geological storage capacity for CO_2 hydrates in Southeast Hainan, it is assumed that the injected CO_2 gas component is pure CO_2, and the influence of other components is not considered. The gas component information is integrated into the CSMHyd software, and the corresponding CO_2 hydrate equilibrium pressures at different temperatures are shown in Table 2.

Based on the virtual well coordinates presented in Table 1, Eqs. (1)-(5) are used to determine the water depth, seabed pressure, seabed temperature, and geothermal gradient values at each well location and establish the stable region CO_2 hydrate storage model for each well (Fig. 3). According to our measurement, the seawater temperature (T_w) decreases with water depth; at a water depth of 415 m below the sea surface, it is approximately 9.9 °C. This aligns with the boundary of the CO_2 phase, where it exists in a gaseous state. The solid hydrate phase develops at depths at or below 415 m (Fig. 2); that is, the minimum water depth conducive to CO_2 hydrate storage is 415 m under ambient temperature and pressure conditions in southeastern Hainan. According to the CO_2 hydrate phase equilibrium distribution characteristics determined at 18 different structural units, it is found that the structural units in southeastern Hainan are conducive to the storage of CO_2 hydrate at water depths greater than 415 m. Our model shows that the effective thickness of the stable CO_2

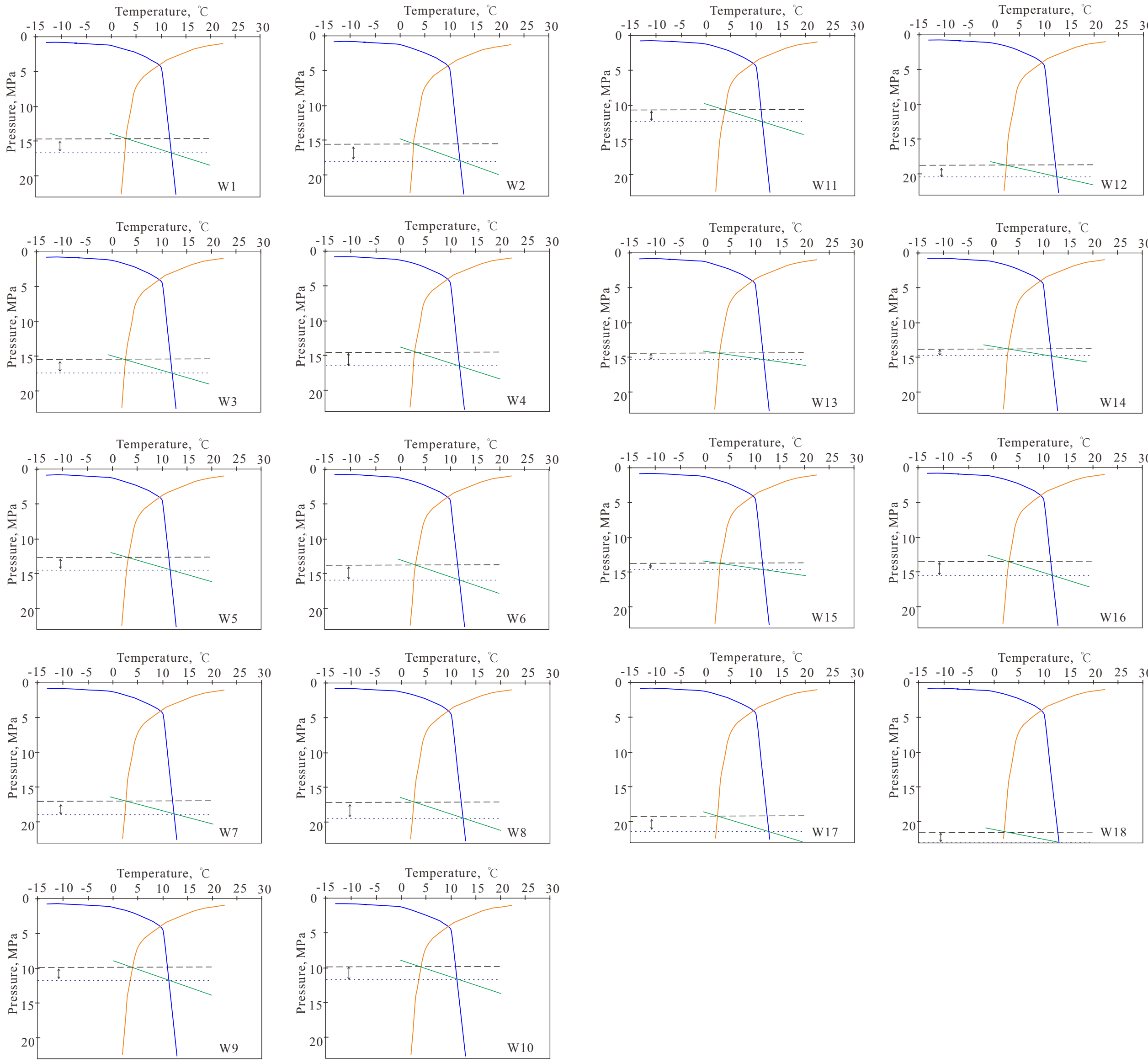

Fig. 3. Phase equilibrium distribution characteristics of CO_2 hydrates in 18 virtual wells of each structural unit in the QDNB.

hydrate storage region in 18 wells is greater than 80 m, and W15 exhibits the smallest favourable storage thickness, mainly due to the shallow water depth and high temperature gradient. The thickness values of the CO_2 hydrate storage stability zone and the main parameters of all 18 wells are shown in Table 3.

After determining the thickness values of stable CO_2 hydrate zone in the 18 wells, the seabed topography within the study area was surveyed via a multibeam echosounder, to obtain the water depth distribution (Fig. 4). The seabed temperature distribution (Fig. 5(a)) and temperature gradient distribution (Fig. 5(b)) in the study area were determined by linear interpolation, which was obtained from the GHFD and the temperature measurement data of 18 virtual wells. The distribution of seafloor temperature shows that the northern depression to the central uplift, the central depression to the southern uplift and the southern depression of the QDNB gradually present the trend of temperature reduction, while the temperature gradient shows the opposite trend. Meanwhile, some high temperature gradient areas exist, such as in the central depression. The temperature gradient, seafloor temperature and water depth changes significantly influence the potential area of stable CO_2 hydrate storage.

Using the minimum water depth of 415 m necessary for CO_2 hydrate formation in the QDNB as a constraining factor, the effective distribution area for CO_2 hydrate storage can initially be outlined. Than, according to the established seabed temperature and temperature gradient distribution in the study area (Fig. 5), the CO_2 hydrate phase equilibrium curve is constructed point-by-point to determine the storage thickness distribution of the CO_2 hydrate (Fig. 6). The findings indicate that the available storage thickness in the eastern Songnan Sag and Songnan low lift is relatively high, with a maximum value of nearly 300 m. The average storage thickness in the study area is 127.9029 m, and the effective CO_2 hydrate storage area

Table 3. Key parameters of virtual wells and thicknesses of the CO_2 hydrate storage stability zone.

No.	Well	Depth of water (m)	Pressure (MPa)	Temperature (°C)	Temperature gradient (°C/100 m)	Storage thickness (m)
1	11	1,447.2	14.5556	3.2	44.3	203.2702
2	12	1,547.1	15.5604	3	37.2	252.5091
3	13	1,530.5	15.3934	3	47.9	194.5396
4	14	1,446.4	14.5475	3.2	46.1	204.0702
5	15	1,252	12.5923	3.5	47.8	189.6758
6	16	1,365	13.7288	3.3	42	215.8720
7	17	1,688.7	16.9845	2.8	52.9	190.4498
8	18	1,714.2	17.2410	2.8	45.9	214.6627
9	19	975.4	9.8103	4.2	43	200.8086
10	20	959.7	9.6524	4.3	45	193.6406
11	21	1,041	10.4701	4	46	186.9100
12	QDN-W-01	1,851	18.6219	3	65	166.8461
13	QDN-W-07	1,422	14.3021	3	103	94.2452
14	QDN-W-08	1,378.5	13.8646	3	102	93.0035
15	QDN-W-09	1,361	13.6886	3	113	80.6758
16	5	1,335.8	13.4351	3.5	44	215.2443
17	18	1,908	19.1902	2.7	47	229.6572
18	19	2,154	21.6644	2.4	63	172.5664

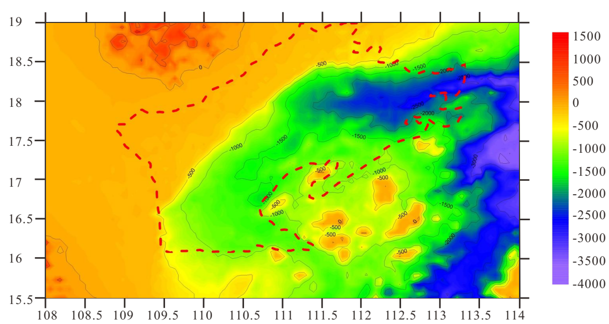

Fig. 4. Water depth distribution in the study area.

is 5.16×10^4 km^2, which contains abundant storage areas with favourable locations and good storage potential.

After determining the effective CO_2 hydrate storage area and the storable thickness of CO_2 hydrate in the QDNB, the storage capacity can be calculated by Eq. (6). The value of E, according to Jenkins and others, is suggested to be in the range of 0.56 to 0.84, based on global depleted gas fields (Jenkins et al., 2012; Zhang et al., 2022). Accordingly, the roughly estimated potential of CO_2 hydrate storage in the QDNB is in the range of 5.75×10^{11}-8.73×10^{11} t, for which the value range of E is between 0.56 and 0.85.

5. Discussion

In recent decades, geological surveys and exploration efforts in southeastern Hainan Province have uncovered an array of substantial gas fields and condensate deposits, mainly originating from Palaeogene source rocks deposited along the transitional environment between land and sea (Xie et al., 2019). A drilling survey of shallow sediments and natural gas hydrates was also carried out by the Guangzhou Marine Geological Survey in 2018 (GMGS5) and 2021 (GMGS6), accumulating abundant drilling and logging data, which provides the research basis for this study. Five key parameters (Eq. (6)) are needed to evaluate the storage potential of CO_2 hydrate by the volumetric method. Among them, the effective storage area of CO_2 hydrate and storable thickness can be determined by the phase equilibrium equation and are related to temperature, temperature gradient, pressure, and water depth. Among the other three parameters, formation porosity is established according to drilling cores and logging data in southeastern Hainan Province (Zhu et al., 2023). In the evaluation of gas hydrate saturation, the density logging curve is often used to calculate porosity (Collett and Ladd, 2000; Zhou et al., 2023), which is also employed in this work. Density porosity (ρ) can be written as: $\varphi = (\rho_m - \rho)/(\rho_m - \rho_w)$, where denotes the density of density logging curve, denotes the density of seawater that equals 1.03 g/cm^3, and denotes the matrix density that equals 2.65 g/cm^3. Fig. 7 presents the change in the response value of the main logging curve and the porosity distribution in the CO_2 hydrate storage stability zone of well W14 in the study area. The stable area (yellow area in the figure) is determined in combination with the phase equilibrium mechanism, and the porosity of the drilling cores

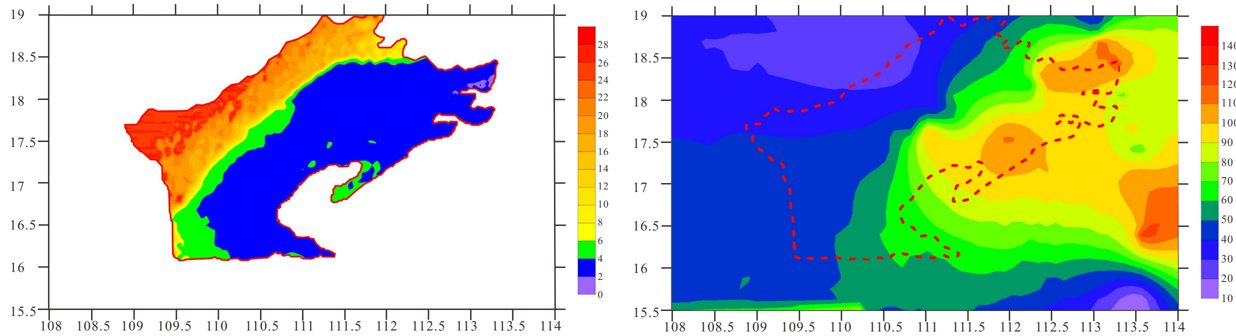

Fig. 5. Seabed temperature and temperature gradient distribution in the study area: (a) Seabed temperature distribution and (b) temperature gradient distribution.

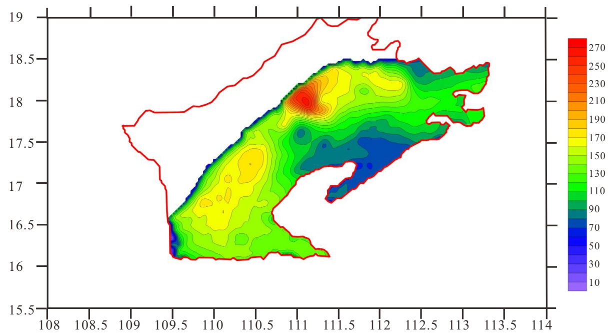

Fig. 6. Thickness distribution of CO_2 hydrate storage stable zone in the study area.

(Wei et al., 2019) is shown in the last line of Fig. 7. According to the statistical results, the variable range of porosity of drilling cores is mainly between 38% and 62%. Drawing on drilling surveys in the study area, the porosity calculated from logging data obtained from the exploration wells matches the trend of core porosity, and the average porosity is determined as 56%.

In contrast to the classical estimation method of storage potential proposed for the saltwater layer, the key parameters of this study are determined by actual drilling data, and factors such as temperature, pressure and water depth are considered in the storage capacity calculation formula. The effective thickness of CO_2 hydrate storage is reasonably restricted, the sediment-free area is removed, and the actual phase equilibrium model is used. The results are more objective and accurate compared to previous models. Of note, this model is only applicable to calculating the theoretical geological storage capacity of CO_2 hydrate storage; for other types of marine CO_2 storage potential evaluation, further and more targeted research is necessary.

6. Conclusions

1) Building on the most recent research advancements and basic parameters garnered from drilling in Southeast Hainan, this study evaluated the theoretical storage capacity of CO_2 hydrate in Southeast Hainan, which was found to meet the temperature and pressure conditions for the storage of CO_2 within sediments. The roughly estimated potential of CO_2 hydrate storage in the QDNB is in the range of 5.75×10^{11}-8.73×10^{11} t, with a value range of E between 0.56 and 0.85.
2) Supported by multibeam bathymetry, the seabed temperatures and pressures of 18 virtual wells, the distribution of the stable CO_2 hydrate storage zone was outlined, the effective thickness and regional range of CO_2 hydrate storage in southeastern Hainan were determined, and the CO_2 hydrate storage potential was evaluated using the combination of phase equilibrium mechanism and volumetric method. The findings indicate that, under the prevailing temperature and pressure conditions in southeastern Hainan, the minimum water depth favorable for CO_2 hydrate storage is 415 m. The effective thickness of the CO_2 hydrate storage stable zone in 18 wells is greater than 80 m, and the average thickness is 183 m. These data support a more dependable foundation for China in shaping strategies for the implementation and advancement of CO_2 hydrate storage.

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Conflict of interest

The authors declare no competing interest.

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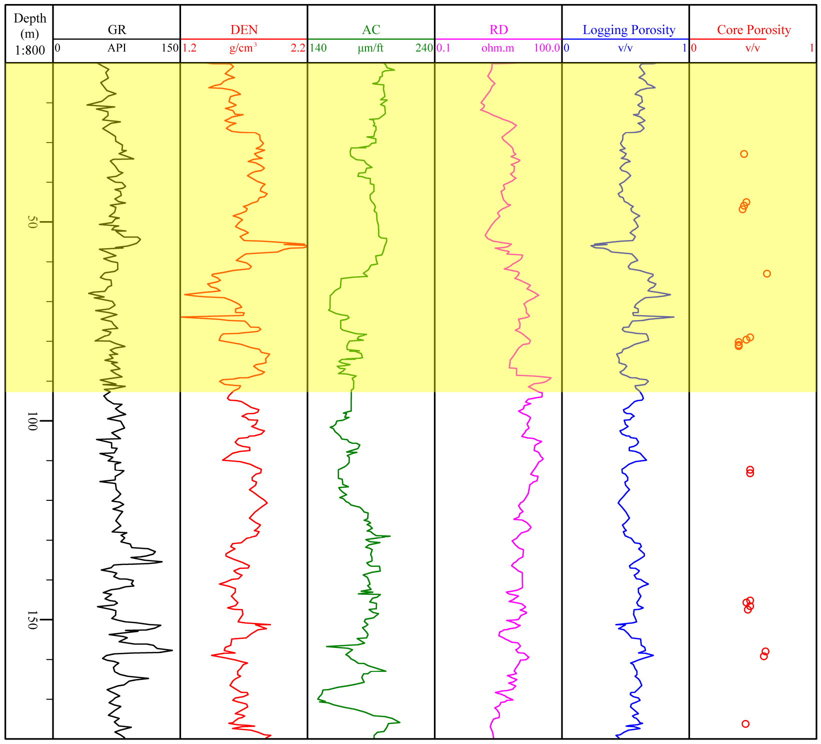

Fig. 7. Logging response and the porosity of drilling cores in the CO_2 hydrate storage stable zone of W14 in the study area (GR represents natural gamma logging curve; DEN represents density logging curve; AC represents acoustic logging curve; RD represents resistivity logging curve; Logging Porosity represents porosity logging curve, which is calculated from the density logging curve; Core Porosity represents the porosity of drilling cores).

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