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Geological Conditions and Suitability Evaluation for CO₂ Geological Storage in Deep Saline Aquifers of the Beibu Gulf Basin (South China)

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Abstract: The geological storage of carbon dioxide (CO₂) is the most suitable option to achieve a large-scale and low-cost CO₂ emissions worldwide, but the selection of favorable areas for the geological storage is the main issue. In this study, evaluation indicators were selected considering four aspects, namely geological conditions, storage potential, hydrogeological conditions, and engineering conditions, based on drilling, geophysical, and geochemical data from the Beibu Gulf Basin. The analytical hierarchy process and the fuzzy comprehensive evaluation method were used to evaluate the suitability of this basin for geological storage of CO₂. The results suggested that: (1) the Beibu Gulf Basin is suitable for CO₂ geological storage, and the evaluation grade is the highest rating level; (2) considering the techno-economic feasibility, it is necessary to select the target area for CO₂ geological storage with suitable burial depth, superior reservoir conditions, proximity to the CO₂ collection device, and a high degree of exploration.

Keywords: CO₂ geological storage; Beibu Gulf Basin; analytic hierarchy process; fuzzy comprehensive evaluation; suitability evaluation



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1. Introduction

With the excessive emission of CO₂, the greenhouse effect has remarkably intensified, and global climate change is one of the most serious challenges [1,2]. The key technologies for reducing CO₂ emissions are carbon capture, use, and storage (CCUS or CCS) [3,4]. Research on CO₂ geological storage has become a focus area in geological exploration [4,5]. CO₂ geological storage technology is a promising technology for achieving a dual-carbon target in China [6–10]. The scientific principle of CO₂ geological storage involves the injection of supercritical CO₂. When the temperature is higher than 31.1 °C and the pressure is higher than 7.38 MPa, CO₂ enters the supercritical state, into saline aquifers in sedimentary basins, depleted oil and gas fields, and coal seams without commercial exploitation value [11–14]. Therefore, the burial depth of saline aquifers that store CO₂ should generally be ≥800 m. In addition, there must be high-quality reservoirs for large-scale CO₂ storage near storage sites, and stable regional caprocks (or aquifers) above the reservoirs to prevent direct leakage of CO₂ [7]. Recent studies showed a huge potential for geological storage of CO₂ in deep saline aquifers in China, accounting for 96.6% of the storage potential, far exceeding that of oil fields, natural gas fields, and coalbed methane fields. It can be considered the primary pathway to realize large-scale CO₂ geological storage in China [8,15–18].

The CO₂ emissions from coastal cities in China have been increasing with continuous economic development. However, due to the small scale, poor reservoir quality, and dense population of adjacent land, it is not suitable for long-term storage of large amount of

CO₂ [10]. In contrast, a series of large sedimentary basins are developed in offshore areas of China, with sufficient sedimentary thickness, relatively good combinations of reservoir and cap rock, well-developed traps, and favorable geological conditions for CO₂ storage. The theoretical storage capacity of deep saline aquifers in China is 143.5×10^9 t; among them, the storage potential of marine sedimentary basins, eastern continental basins, western continental basins, central continental basins, southern continental basins accounted for 27.33%, 31.88%, 20.33%, 10.49%, and 9.97% of the total potential, respectively [10,18,19]. In addition, saline aquifers in the sedimentary basin are widely distributed, stable, and have great storage potential, which confirms their suitability for implementing offshore CO₂ geological storage. The Beibu Gulf Basin is located to the south of Guangxi Province and is a Cenozoic petroliferous basin with a large offshore area in China that provides potential conditions for CO₂ geological storage. Therefore, it is important to further analyze the suitability of the geological storage of carbon dioxide in the area.

Owing to more than half a century of oil and gas exploration, a series of small- and medium-sized oil and gas fields and oil-bearing structures have been discovered in the Beibu Gulf Basin, which have been put into development and production, becoming a major oil and gas source in the shallow-water area of the northern continental shelf of the South China Sea. More than 100 exploration wells have been drilled in the Weixinan, Haizhong, and Wushi Sag in the Northern Depression, but most exploration activities are concentrated in the Weixinan Sag [20,21]. The Beibu Gulf Basin is an area to be evaluated due to its low degree of exploration and relatively limited data. Therefore, the implementation of CO₂ geological storage technology in the Beibu Gulf Basin can effectively alleviate the pressure of CO₂ emission reduction in neighboring provinces, which is important to achieve CO₂ emission reduction targets. Studies on the suitability of quantitative CO₂ geological storage in basins are still in the exploratory stage. In this study, the deep saline aquifer in the Beibu Gulf Basin was used as the case study, and the geological conditions, reservoir-cap rock characteristics, geothermal field characteristics, and hydrogeological conditions of the geological storage in this area were investigated. Based on the evaluation of its storage conditions, the analytic hierarchy process and the comprehensive fuzzy evaluation method were used to quantitatively evaluate the suitability of CO₂ geological storage in the deep saline aquifer in this area, which provides technical support for the next step of potential evaluation, target area screening, site selection, and demonstration project construction. This study has an important exploration significance for China to achieve low-carbon emission and carbon neutrality.

2. Geological Conditions of Geological Storage in the Beibu Gulf Basin

2.1. Regional Geological Characteristics

The Beibu Gulf Basin, with an area of 5.15×10^4 km², is adjacent to the Leizhou Peninsula and Hainan Island in the east, the Yunnan-Guizhou Plateau in the north, and Hainan Island in the south. The seabed topography of the Beibu Gulf Basin is flat and the seawater depth is shallow, ranging from 0 to 55 m, with characteristics of shallow north and deep south.

The Beibu Gulf Basin is located in the Red River strike-slip fault zone between the Guangdong-Guangxi Paleozoic fold belt and the Hainan fold belt at the southern end of the Yangtze plate. It is an intracontinental rift basin formed under the background of Cenozoic intracontinental extensional tectonic development. It is divided into three secondary tectonic units, namely the southern Depression, the Qixi Uplift, and the northern Depression. It is mainly composed of seven sags, namely, Weixinan, Wushi, Maichen, Haizhong, Leidong, Fushan, and Haitoubei [22] (Figure 1). The Beibu Gulf Basin has primarily experienced the Shenhui, South Sea, and Dongsha movements, forming a typical double-layer basin structure of first fault and then depression. The present basin structure reflects the superposition effect of multistage tectonic movements [21,23] (Figure 2). From the Early Jurassic to the Paleogene, the Beibu Gulf Basin was in a long-term uplift state and suffered from denudation. Influenced by the expansion of the South China Sea and

the activities of the surrounding boundary faults in the Paleogene, an extensional fault depression occurred and gradually evolved into the present tectonic framework of the Beibu Gulf Basin [24].

As the Beibu Gulf Basin is close to the edge of the plate, affected by collision and separation, its tectonic activity is slightly stronger and faults are developed primarily in the NE and NEE directions [25]. The primary nature of the fault is a normal fault, developed entirely in the early Paleogene, the Beibu Gulf tension crack, resulting in rift and basin formation. By the early Neogene, fault activities had stopped. The major faults developed constituted the boundary of the basin and control the development of secondary tectonic units in the basin.

Earthquake activity is strongest in the plate suture zone or plate edge [26,27]. The crust of the Beibu Gulf Basin is relatively stable, and there was weak seismic activity in the early Quaternary. Only one earthquake with a magnitude of 6–7 occurred in the north of the South China Sea.

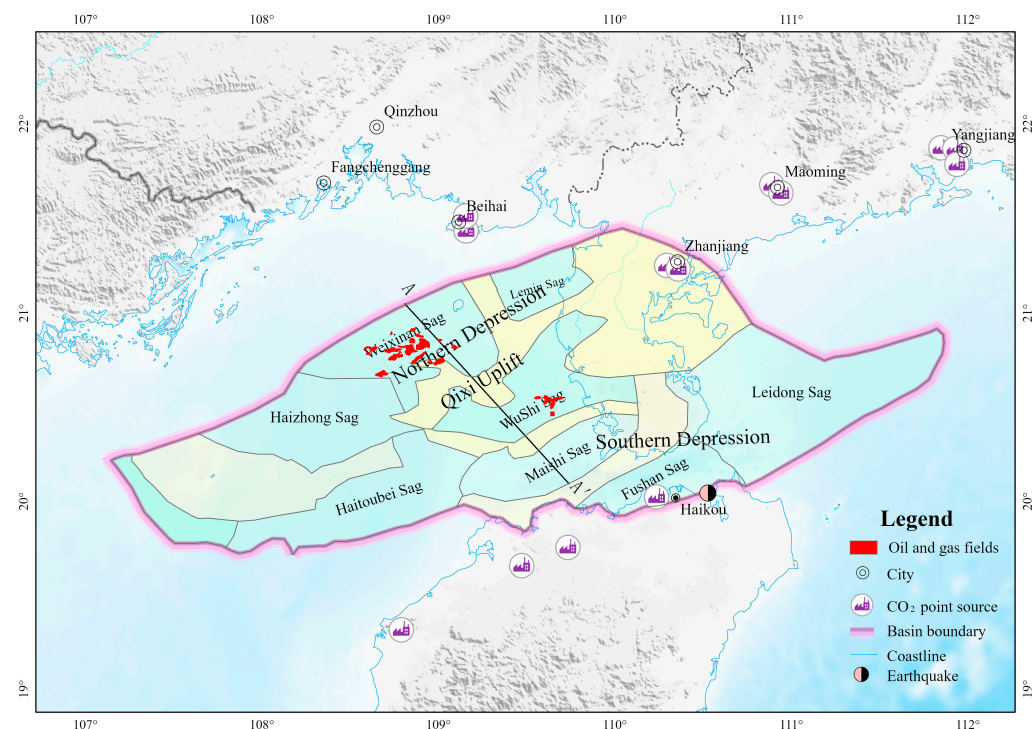


Figure 1. Simplified geological map of the Beibu Gulf Basin (modified after [28,29]) showing locations of structure units, oilfields, earthquake epicenters, and CO₂ emission point sources.

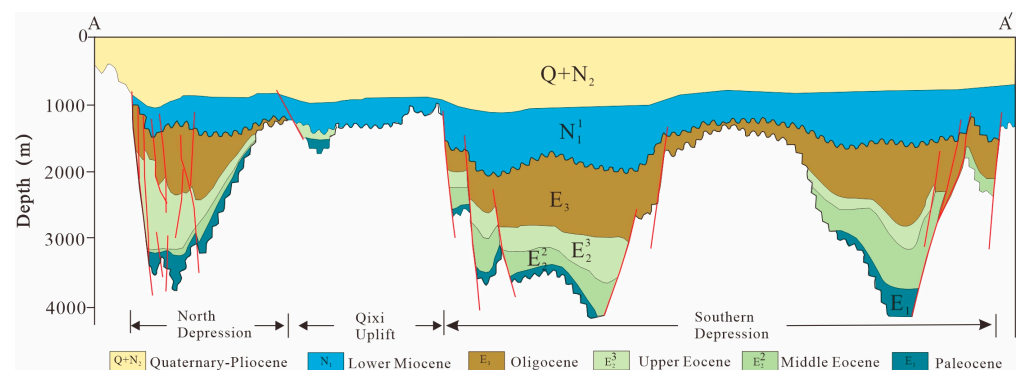


Figure 2. Geological section of the Beibu Gulf Basin (modified after [28]). See Figure 1 for the profile location.

2.2. Stratigraphic Characteristics

The formation and evolution of the Beibu Gulf Basin showed the characteristics of first faulting and then depression [30]. During the Paleogene continental fault depression period, the Paleocene, Eocene, and Oligocene (Changliu Formation) Liushagang Formation, and Weizhou Formation, were dominated by fluvial-lacustrine half-graben deposits. These deposits are primarily filled with shallow lacustrine facies, semi-deep or deep lacustrine facies, and fluvial facies, forming lacustrine and coal source rocks and continental reservoir-caprock assemblage types. During the periods of thermal subsidence of the Miocene and Pliocene, the basin primarily deposited the Lower Miocene Xiayang Formation, Miocene Jiaowei Formation, the Upper Miocene Denglougiao Formation, and the Pliocene Wanglougang Formation [31].

2.3. Reservoir-Caprock Characteristics

The Beibu Gulf Basin has experienced a complete sedimentary cycle from the appearance, development, and extinction of the lake basin in the Paleogene, and the whole area of the Neogene underwent a marine transgression to form a marine sedimentary cycle, which controlled the formation of multiple reservoir-cap associations. Reservoirs are widely distributed in the Beibu Gulf Basin, comprising sandstone and carbonate rocks [32], and sandstone reservoirs are mainly composed of sandstones deposited in braided river deltas, fan deltas, meandering river deltas, sublacustrine fans, and littoral-neritic facies [21]. These can be further divided into the Neogene marine sandstone reservoirs and the Paleogene continental sandstone reservoirs. Marine sandstone reservoirs are mainly marine sandstones of the Miocene Xiayang and Jiaowei Formations with over 20% porosity, several hundred millidarcies of permeability, and the highest can exceed 10,000 millidarcies, showing relatively good reservoir properties [33–35]. In contrast, the continental sandstone reservoirs are mainly lacustrine sandstones of the Eocene Liushagang Formation and the Oligocene Weizhou Formation. The porosity was 15–35%, and the permeability was $40\text{--}3000 \times 10^{-3} \mu\text{m}^2$, with good reservoir properties [36,37]. The thick mudstones developed into different layers, such as the Eocene Liushagang Formation, Oligocene Weizhou Formation, and Miocene Jiaowei Formation, can be used as regional caprocks. The Liushagang Formation is dominated by semi-deep lacustrine-deep lacustrine deposits, and the Weizhou Formation is dominated by delta-shallow lacustrine deposits, with a large set of semi-deep lacustrine-deep lacustrine mudstone developed. During the deposition period of the invasion of the Liushagang Formation, the lake reached its maximum, and thick dark mudstone was deposited almost throughout the depression, forming an important set of regional cover in the Beibu Bay Basin, with a maximum thickness of 350 m.

According to the distribution characteristics of reservoir-caprock assemblages, the Beibu Gulf Basin can be divided into two sets of effective reservoir-caprock combinations. The river-marsh facies and shallow lake facies sandstones of the Liushagang Formation are good reservoir-caprocks, and the river-marsh facies and littoral-neritic facies sandstones of the Weizhou Formation–Xiyang Formation are relatively good reservoir-caprocks (Figure 3).

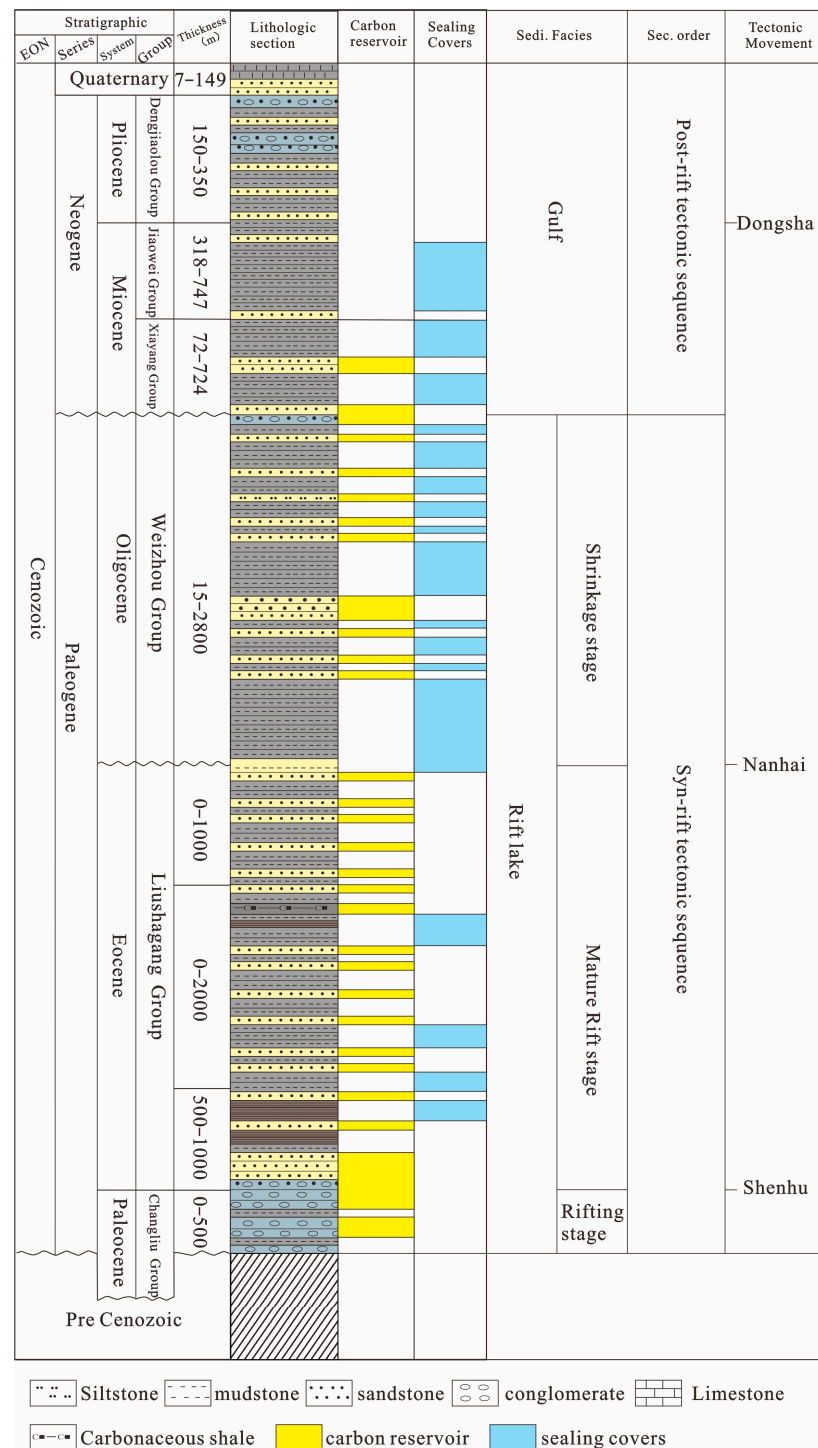


Figure 3. Reservoir-caprock assemblages of the Beibu Gulf Basin.

2.4. Geothermal Field Characteristics

The geothermal gradient of the strata in different offshore areas of China is considerably different, and that in the stable continental shelf area is low. In the deep-water area, the geothermal gradient was higher, and the basin was relatively hot. The geothermal gradient is high in the northern South China Sea due to the strong thermal effect of the deep high-temperature mantle on the continental margin [36,38]. The Beibu Gulf Basin has a high geothermal gradient, with an average geothermal gradient reaching 3.72 °C/100 m. However, the geothermal characteristics of different depressions vary considerably, and

their regional distribution is remarkably uneven. The average geothermal gradient of the Weixinan, Haizhong, Wushi, and Haitoubei sags is 3.86, 3.35, 3.50, and 3.25 °C/100 m, respectively [39]. Basins with geothermal gradients lower than 30 °C/km can be classified as cold basins, basins with geothermal gradients between 30–50 °C/km can be classified as sub-cold-sub-hot basins, and basins with geothermal gradients greater than 50 °C/km can be classified as hot basins [40]. The Beibu Gulf Basin is classified as a sub-cold-sub-hot basin.

Heat flow refers to heat transferred from the interior of the Earth to the surface of the Earth per unit area per unit time. Compared to other geothermal parameters, terrestrial heat flow can more accurately reflect the characteristics of the geothermal field [41]. Overall, the terrestrial heat flow value in the northern part of the South China Sea is 60–80 mW/m², whereas the average terrestrial heat flow in the Beibu Gulf Basin is 61.7 mW/m² [42]. The terrestrial heat flow in the Beibu Gulf Basin is affected by plate movement and generally presents a high distribution pattern in the northeast (70–100 mW/m²) and a low distribution pattern in the southwest (50–70 mW/m²) (Figure 4).

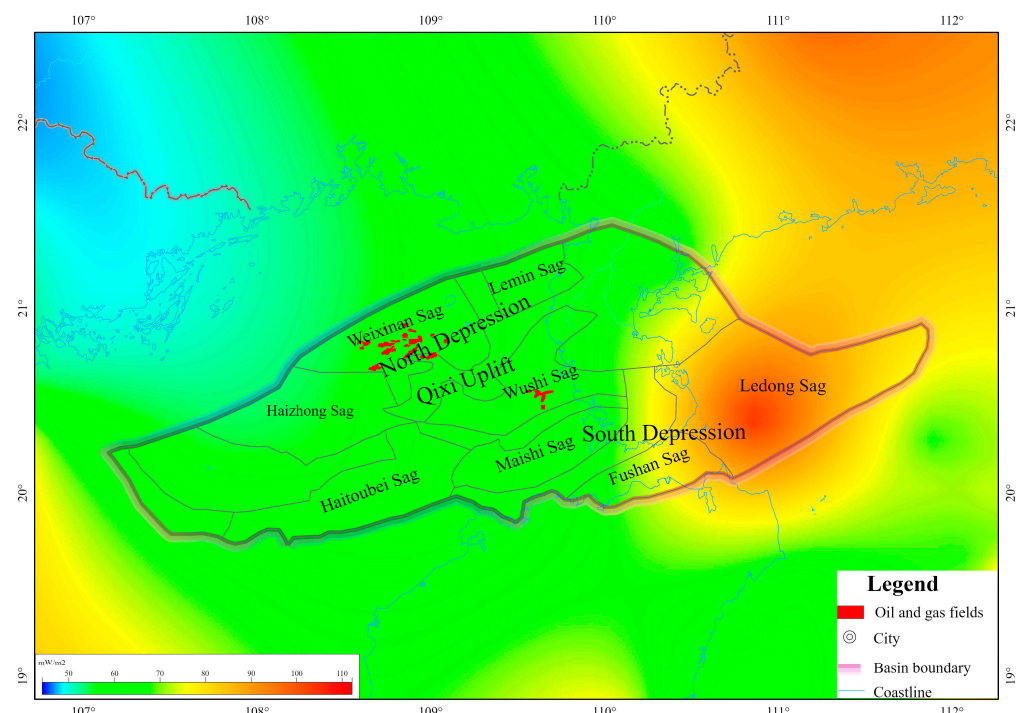


Figure 4. Characteristics of the geothermal field in the Beibu Gulf Basin.

2.5. Hydrogeological Conditions

The process of CO₂ storage in the reservoir is affected by numerous factors, such as the temperature and pressure conditions of the rock strata and geochemistry, which are primarily related to the hydrogeological characteristics of sedimentary basins [43]. Therefore, appropriate hydrogeological conditions are also necessary for safe storage of CO₂ [44,45]. The ion content in formation water can be used to analyze the chemical composition, formation conditions, and influencing factors of formation water, and to understand the interactions between formation water and rocks.

The results of oilfield formation water analysis in the Beibu Gulf Basin showed a salinity of 5.60–39.50 g/L, close to that of modern seawater (35 g/L), and thus there is no obvious vertical zonation (Table 1). In the conventional ion combination, the study area is relatively rich in HCO₃[−] and poor in SO₄^{2−}, rich in Ca²⁺, and poor in Mg²⁺. The contents of Na⁺ and K⁺ were much higher than those of Ca²⁺ and Mg²⁺, and the content of Cl[−] was much higher than SO₄^{2−} and HCO₃[−]. The proportions of Na⁺, K⁺, and Cl[−] were high and obviously higher than the mass concentration of the present seawater, which indicates that the formation water type is mainly NaCl.

In addition, the combined characteristics of various chemical parameters of oilfield formation water reflect the characteristics of oil and gas accumulation and preservation. The sodium chloride coefficient (rNa^+ / rCl^-) is the key parameter that reflects the formation sealing and metamorphic degree of oilfield water. If the sodium chloride coefficient is greater than 0.87, and the salinity is high, it may be sedimentary water or metamorphic seepage water; if the sodium chloride coefficient is less than 0.87, it may be metamorphic sedimentary water or highly metamorphic permeable water [46–48]. It is generally believed that the better the sealed formation water is, the more concentrated it is. When the depth of metamorphism is, the smaller the sodium chloride coefficient (Na^+ / Cl^-) ratio, the more conducive it is to oil and gas preservation. The sodium chloride coefficient of the Beibu Gulf Basin is between 0.66 and 0.74, with a low sodium chloride coefficient, indicating that the formation water is well sealed. Based on hydrogen and oxygen isotope analysis of the formation water in the Beibu Gulf Basin, the formation water originates from seawater, which may be the same generation and sedimentation water directly buried in the sea. During its evolution, the formation water experienced little evaporation and precipitation recharge [49]. According to the analysis of formation water characteristics in the Beibu Gulf Basin, the internal and external water are independent of each other and are affected by fluid-rock interaction and concentration metamorphism, forming the typical characteristics of relatively closed, lack of supply, and high mineralization. To some extent, this shows that the target intervals of the Beibu Gulf Basin belong to a relatively closed formation water environment, which is another favorable factor for safe and effective CO₂ storage.

Table 1. Results of the chemical composition analysis of formation water in main target carbon reservoirs of the target in the Beibu Gulf Basin (modified after [49]).

Region	Na ⁺ + K ⁺	Ca ²⁺	Mg ²⁺	Cl [−]	SO ₄ ^{2−}	HCO ₃ [−]	Mineralization/ (g·L ^{−1})	Style of Formation Water
	mg·L ^{−1}							
Weixinan Sag	11,718.20	1572.00	252.78	25,506.27	96.06	233.00	39.50	NaCl
	7374.40	1117.50	148.26	15,739.80	878.94	315.53	25.61	NaCl
	7526.05	810.00	419.27	14,924.451	248.78	194.17	25.54	NaCl
	9369.70	1566.50	221.18	21,092.75	182.51	306.43	32.98	NaCl
	2100.1	107	34.4	1712.7	164.6	2871.5	7.01	NaHCO ₃
	1504.9	40.1	6.6	947.7	131.7	2297.3	5.60	NaHCO ₃
	9757	671	547	16,819	1152	293	29.25	CaCl ₂
Wushi Sag	9062.23	321.24	39.51	13,470.37	362.21	1398.51	24.74	NaCl
	11,672.5	284.6	32.8	12,107.2	4963.9	4600.7	33.78	NaCl
	7872.21	156.31	51.06	9108.58	2667.16	2323.53	22.29	NaCl
	6891.72	153.91	46.68	7965.23	2197.22	141.62	19.59	NaCl

3. Materials and Methods

3.1. Data Sources

The data used in this study were derived from the published literature. In 2010, the Cenozoic isopach map and the structural map of the Atlas of Petroleum Basins in China's Seas were published. The degree of oil and gas exploration and development of the basin and the physical parameters of the reservoir in the mineral right block were obtained primarily from the public literature published by commercial oil companies and scientific research institutes. Ground temperature field data were obtained from the official website of the International Heat Flow Commission (IHFC). The drilling, oil, and gas field details were sourced from China's offshore oil and gas information management system.

3.2. Analytical Hierarchy Process (AHP) and Fuzzy Synthetic Evaluation Method

During the analysis of carbon dioxide geological sequestration factors, it was found that suitability evaluation is affected not only by qualitative factors, such as structural characteristics, exploration degree, and volcanic activity, but also by quantitative factors

such as reservoir thickness, reservoir physical properties, and offshore distance. To research the influence of qualitative and quantitative factors, a composite method combined with an AHP and fuzzy synthetic evaluation was used to assess the suitability of geological storage. The method assigns the correct weight coefficients to different influencing factors and establishes a mathematical model among the evaluation result (B) of the single factor evaluation standard matrix, weight coefficient (W), and the evaluation score (R) using Equations (1) and (2).

$$B = WR \quad (1)$$

$$[b_1, b_2, \dots, b_i, \dots, b_n] = [w_1, w_2, \dots, w_i, \dots, w_m] \times [r_{ij}]_{mn} \quad (2)$$

Using the fuzzy synthetic evaluation method to conduct qualitative and quantitative grade evaluations for each factor, objective, and reasonable evaluation results can be obtained [50,51]. In this composite evaluation model, a reasonable hierarchical structure was established using the AHP method and a pairwise judgment matrix was established using the expert scoring method. After normalization processing and consistency analysis, an unreasonable matrix was excluded, and other weight matrices were averaged to obtain the final weight of each element. The fuzzy synthetic evaluation method was then used to determine the evaluation level criteria for each factor according to the hierarchy established using the AHP method. According to the actual experiment or usage, the index level was judged using the expert scoring method and the evaluation result set was established through the calculation of the membership degree. Finally, the weight of each factor and its grade weight were combined, and the grade judgment of the target layer was obtained according to the principle of the maximum membership degree. Considering the deterministic and uncertain factors, the weight and evaluation of each index were determined to obtain a comprehensive quantitative evaluation result.

3.3. CO₂ Storage Evaluation System

The suitability evaluation of CO₂ geological storage is based mainly on three aspects including the preconditions for storage, the importance of storage, and stability of CO₂ under storage. Based on previous studies on carbon storage, carbon storage site selection evaluation and CO₂-fluid-rock reaction [51–55], four first-grade indexes, including geological conditions, storage potential, hydrogeological conditions, and engineering conditions, were selected as the suitability indices for carbon storage in the Beibu Gulf Basin. Each first-grade index includes multiple second-grade indices, including both deterministic indicator factors, such as the burial depth of the reservoir and caprock, and uncertain indicator factors, such as the impact of earthquakes (Table 2).

The suitability evaluation of CO₂ geological storage includes several influencing factors. This study used the analytic hierarchy process to determine the line index factors and then used the fuzzy synthetic evaluation method to research the deterministic and non-deterministic factors to identify the weight and evaluation of each index to obtain a quantitative comprehensive evaluation result.

The evaluation objects were layered to build a hierarchical model, as shown in Table 3. The AHP and the judgment matrix were used to calculate the weights of each evaluation index. The 1–9 scale was used to score the first level based on the importance of the first-level indicators at the target level. The judgment matrix of each first-level index for the target layer was then listed, and the weight of each index of the first level was obtained using the judgment matrix. The weight of the second-level index in the first-level index was obtained similarly. Finally, the second weight matrix was multiplied by the first weight matrix to obtain the weight of each evaluation index.

Table 2. CO₂ geological storage suitability evaluation index system.

First-Grade Indexes	Second-Grade Index	Requirements Conductive to CO ₂ Storage
Geological conditions	Tectonic characteristics	Sedimentary basins in stable or nearly stable continental plates
	Fault	No fault, few faults, or strong fault sealing
	Geothermal gradient	The lower the more favorable
	Heat flow	
	Formation temperature	≥ 35 °C
	Sealing condition	Caprock thickness greater than 150 m
	Earthquake	Earthquake, volcano not developed
	Volcano	
Storage potential	Area	≥ 2500 km ²
	Reservoir thickness	≥ 20 m
	Reservoir buried depth	> 800 m
	Reservoir petrophysical property	Porosity greater than 10%
	Reservoir pressure	Above the critical value of CO ₂ (7.5 MPa)
Hydrogeological conditions	Reservoir formation water type	NaHCO ₃ ; Cl-Ca-Na; CaCl ₂
	Mineralization	3–50 g/L
	Hydrodynamics	Stable
Engineering conditions	Exploration and development degree	Some exploration activities
	Offshore distance	< 300 km
	Water depth	< 100 m

Table 3. Grading table of evaluation index system.

First Level	Second Level	Impact of the Second Level on the First Level
Geological conditions B1	Tectonic characteristics C1	B1 = g1 (C1, C2, C3, C4, C5, C6, C7, C8, C8)
	Fault C2	
	Geothermal gradient C3	
	Heat flow C4	
	Formation temperature C5	
	Sealing condition C6	
	Earthquake C7	
	Volcano C8	
Storage potential B2	Area C9	B2 = g2 (C9, C10, C11, C12, C13)
	Reservoir thickness C10	
	Reservoir buried depth C11	
	Reservoir petrophysical property C12	
	Reservoir pressure C13	
Hydrogeological conditions B3	Reservoir formation water type C14	B3 = g2 (C14, C15, C16)
	Mineralization C15	
	Hydrodynamics C16	
Engineering conditions B4	Exploration and development degree C17	B4 = g2 (C17, C18, C19)
	Offshore distance C18	
	Water depth C19	
Impact degree of the first level on CO ₂ storage suitability A		A = f (B1, B2, B3, B4)

4. Results

4.1. Weight Values for the Indexes

4.1.1. First-Index Weight

The weight of each index at the first level was calculated using the A-B judgment matrix. Because first-level indicators are classified according to the four directions of prerequisites for storage, significance of storage, stability of carbon dioxide in the storage state, and engineering conditions for storage implementation, they can be regarded as four equally important indicators. The judgment matrix is shown in Table A1 (where W is the normalized weight).

4.1.2. Second-Index Weight

Through expert scoring, the relative importance of each index at the same level in the evaluation model was judged, and these judgments were represented using numerical values by introducing appropriate scales to form a judgment matrix.

B1- $C_{i(i=1-8)}$ judgment matrix: Table A2 shows a judgment matrix of the factors that affect geological conditions.

B2- $C_{i(i=9-13)}$ judgment matrix: Table A3 shows a judgment matrix of the factors that affect the storage potential.

The B3- $C_{i(i=14-16)}$ judgment matrix: Table A4 shows a judgment matrix of the factors of hydrogeological conditions.

The B4- $C_{i(i=17-19)}$ judgment matrix: A judgment matrix of the factors influencing the engineering conditions is shown in Table A5.

4.2. Membership in the CO₂ Geological Storage Index

According to the evaluation factor grade standard, the membership function was constructed using ascending (or descending) semi-trapezoidal and rectangular curves. For the quantitative index with a higher value and higher suitability grade, the ascending semi-trapezoidal distribution membership function was used, and for quantitative indicators with smaller values and higher suitability levels, the membership function of the reduced half trapezoidal distribution was adopted. The suitability evaluation set had a continuous interval $[0, 1]$. The suitability grade of the CO₂ geological storage was classified as Grade I $[0.75, 1]$, Grade II $[0.5, 0.75]$, Grade III $[0.25, 0.5]$, and Grade IV $[0, 0.25]$. The membership function of Grade I was the ascending trapezoidal membership function, whereas the membership function of Grade IV was the descending trapezoidal membership function. In addition, the membership functions of Grades II and III were triangular distribution membership functions.

If the membership degree of an indicator was $(0.7, 0.3, 0, 0)$, then the degree of belonging to Grade I was 0.7, and that for Grade II was 0.3. The membership function for each level is shown in Figure 5.

The scoring results of each index are shown in Table A6.

4.3. CO₂ Storage Suitability in the Beibu Gulf Basin

The evaluation matrix and weight of each index were established through the analytic hierarchy process according to the actual situation of the Beibu Gulf Basin. The suitability of CO₂ geological storage in the Beibu Gulf Basin was evaluated by comprehensively considering the geological conditions, storage potential, hydrogeological conditions, and engineering conditions. The results showed that the membership degree of CO₂ geological storage suitability in the Beibu Gulf Basin was $(0.85, 0.09, 0.07, \text{and } 0)$, which is the ascending trapezoid membership function, and the evaluation grade was grade I (Table 4). This indicates that the Beibu Gulf Basin is suitable for CO₂ storage.

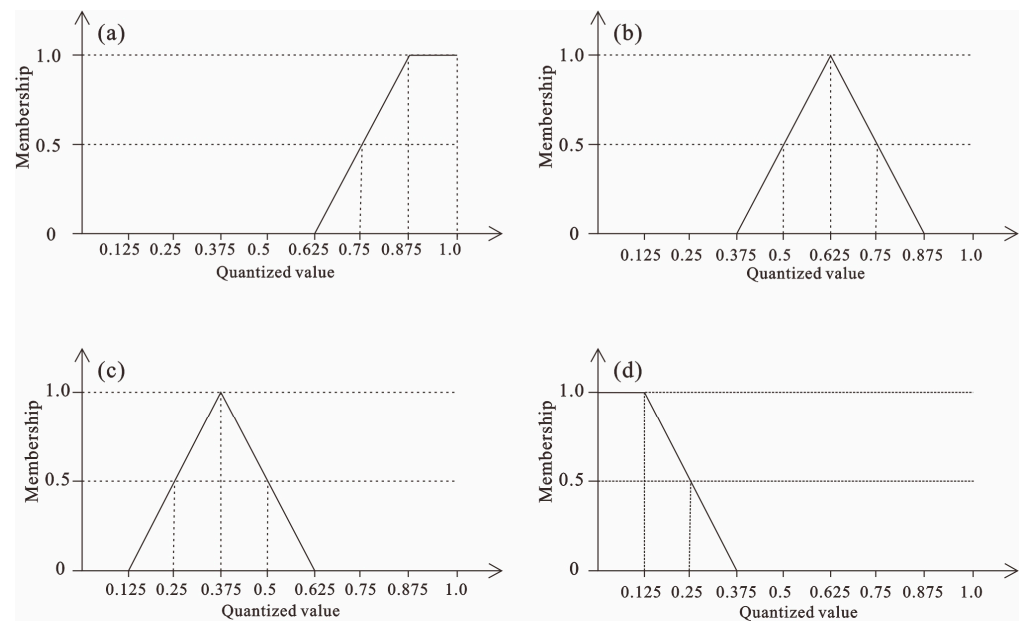


Figure 5. Membership functions at all levels. (a) Grade I membership function; (b) Grade II membership function; (c) Grade III membership function; (d) Grade IV membership function.

Table 4. Results of CO₂ geological storage suitability evaluation.

First Level	Second Level	Comprehensive Index Weight	Membership
Geological conditions B1	Tectonic characteristics C1	$0.25 \times 0.1915 = 0.04788$	(1, 0, 0, 0)
	Fault C2	$0.25 \times 0.0639 = 0.01598$	(0, 0.5, 0.5, 0)
	Geothermal gradient C3	$0.25 \times 0.0639 = 0.01598$	(1, 0, 0, 0)
	Heat flow C4	$0.25 \times 0.1875 = 0.04688$	(1, 0, 0, 0)
	Formation temperature C5	$0.25 \times 0.0327 = 0.00818$	(1, 0, 0, 0)
	Sealing condition C6	$0.25 \times 0.2212 = 0.05530$	(1, 0, 0, 0)
	Earthquake C7	$0.25 \times 0.1778 = 0.04445$	(0, 0.5, 0.5, 0)
	Volcano C8	$0.25 \times 0.0615 = 0.01538$	(0, 0, 0.3, 0.7)
Storage potential B2	Area C9	$0.25 \times 0.2951 = 0.07378$	(1, 0, 0, 0)
	Reservoir thickness C10	$0.25 \times 0.1169 = 0.02923$	(0.7, 0.3, 0, 0)
	Reservoir buried depth C11	$0.25 \times 0.2850 = 0.07125$	(1, 0, 0, 0)
	Reservoir petrophysical property C12	$0.25 \times 0.0514 = 0.01285$	(0, 0.1, 0.9, 0)
	Reservoir pressure C13	$0.25 \times 0.2517 = 0.06293$	(1, 0, 0, 0)
Hydrogeological conditions B3	Reservoir formation water type C14	$0.25 \times 0.5396 = 0.13490$	(1, 0, 0, 0)
	Mineralization C15	$0.25 \times 0.1634 = 0.04085$	(0.7, 0.3, 0, 0)
	Hydrodynamics C16	$0.25 \times 0.2969 = 0.07423$	(1, 0, 0, 0)
Engineering conditions B4	Exploration and development degree C17	$0.25 \times 0.6483 = 0.16208$	(1, 0, 0, 0)
	Offshore distance C18	$0.25 \times 0.2297 = 0.05743$	(0.7, 0.3, 0, 0)
	Water depth C19	$0.25 \times 0.1220 = 0.03050$	(0, 0.5, 0.5, 0)
CO ₂ storage suitability A membership degree (0.84, 0.09, 0.06, 0.01) Grade I			

5. Discussion

CO₂ geological storage is preliminarily screened according to the reservoir, reservoir fluid characteristics, and basic conditions, and the corresponding storage suitability index system is formulated according to the characteristics of the stored geological body and the purpose of the assessment [56,57]. A series of evaluation index systems consider regional geology, storage safety, and environmental risks. Some evaluations in recent years have further considered the health, safety, and environmental risks of CO₂ geological storage [58,59]. Based on the established evaluation indicators, the suitability evaluation of

CO₂ geological storage was conducted by comprehensively considering the technical (reservoir physical properties, temperature, and pressure conditions) and economic (distance from CO₂ capture device, exploration degree, and formation depth) aspects to provide a reference for the site selection of CCUS demonstration projects in China.

5.1. Stratigraphic Depth

During the optimization of favorable areas for CO₂ geological storage, the buried depth of the stratum should not be too shallow, considering the storage effect and storage cost. If the buried depth is too deep, the construction cost will increase sharply, whereas if the buried depth is too shallow, CO₂ leakage may occur. Therefore, it is necessary to select an appropriate burial depth for CO₂ geological storage. Theoretical studies show that the critical temperature and pressure of CO₂ entering the supercritical state are 31.1 °C and 7.38 MPa, respectively [60]. The geological storage of the CO₂ supercritical state requires regional caprocks buried below 800 m, continuous spatial distribution, relatively large thickness, completeness, impermeable rock formation, no penetrating brittle fracture development, and good airtightness [61]. Saline aquifer storage usually requires CO₂ to be stored underground in a supercritical state, as it usually reaches 800 m below the surface to maintain the stability and safety of CO₂ storage. Therefore, the buried depth of the strata must exceed 800 m to ensure that the injected CO₂ is in a supercritical state. The Beibu Gulf Basin contains two sets of carbon-storage layers. The bottom depth maps of the Neogene and Paleogene strata (Figure 6) suggested that such buried depth conditions can ensure that the injected CO₂ is in a supercritical state, which provides favorable buried depth conditions for the effective injection and storage of CO₂.

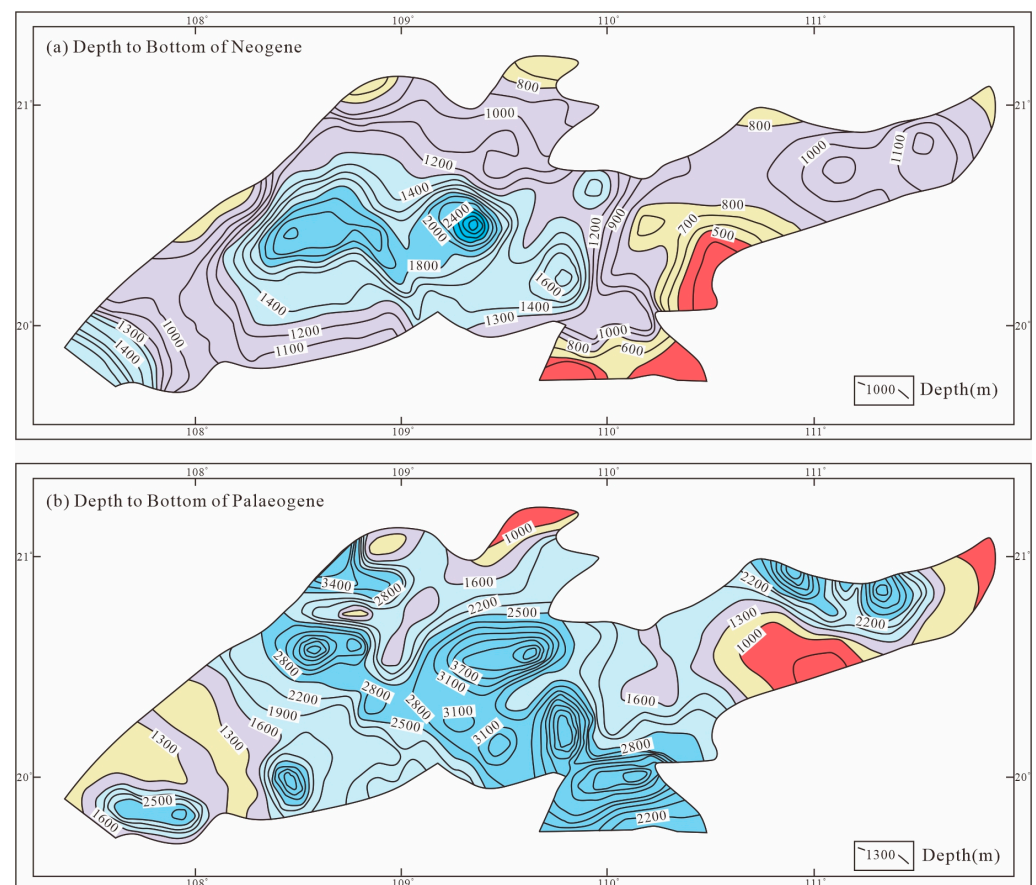


Figure 6. Burial depth map of Neogene (a) and Paleogene (b) strata in the Beibu Gulf Basin (modified after [28]).

5.2. Reservoir Petrophysical Property

The size of the formation storage space is a key factor in determining the amount of CO₂ geological storage. When CO₂ geological storage is favorable, reservoir conditions are one of the most important factors to be considered. The main characterization parameter of reservoir conditions is porosity, which is controlled mainly by diagenesis. The study shows that the Cenozoic strata below 2000 m are in the Eodiagenetic stage [62]. Under compaction and cementation, reservoir porosity decreased with increasing depth. A burial depth of 2000–3200 m is the early stage of Mesodiagenesis. The soluble components of sandstone are dissolved by organic acids, forming numerous secondary pores, thus improving the petrophysical properties of the reservoirs. The porosity of the reservoirs can reach 15–25%. The reservoirs in the Beibu Gulf Basin are dominated by sandstones, with a total thickness of 100–300 m. The porosity is 10–24%, and the permeability is 1×10^{-3} – $13.665 \times 10^{-3} \mu\text{m}^2$. Therefore, it can be considered as a potential carbon dioxide reservoir (Table 5).

Table 5. Reservoir characteristics of the Beibu Gulf Basin (modified after [28,30–33]).

Depression	Formation	Porosity (%)	Permeability (mD)	Facies	Lithology	Depth (m)
Weixinan	Liushagang	26.65–29.74	423–673	shallow lake Fan delta	Coarse sandstone, sandy conglomerate	1800–2100
Maichen	Weizhou	23.32–30	234.7–689.1	River delta front	Sandy conglomerate	1300
	Liushagang	15–25	760	River delta	Gravel sandstone, siltstone	2000
Haizhong	Liushagang	7.8	0.4–3	River delta, fan	fine sandstone Mudstone with minor siltstone	2000–4000
	Weizhou	20–24	230–610		Siltstone, sandstone	1000–2000
Fushan	Liushagang	13–18		Fluvial, fan delta	Siltstone, locally sandy	1000–2500
	Weizhou	5.2–33	0.04–6930	shallow lacustrine Fluvial fan and plain	conglomerate Blocky sandy conglomerate	
Leidong	Weizhou	13–17	44–188	Lacustrine, alluvial plain	Sandstone and conglomerate	1300
Wushi	Liushagang	15–25	1–760	River, coastal	with mudstone and silty mudstone interlayer	3000
	Weizhou				Mudstone with shale and sandstone interlayer Sandstone with mudstone	

5.3. Temperature-Pressure Conditions

PetroMod (2016) software was used to construct a basin model to simulate the hydrocarbon generation, expulsion, and accumulation processes of Cenozoic source rocks in the Beibu Gulf Basin. The main input parameters included formation thickness, lithology, geological age, denudation event, surface temperature, geothermal gradient, and boundary conditions of the hydrocarbon-bearing system, such as heat flow, paleo-water depth, and sediment-water interface temperature.

The Beibu Gulf Basin is located in the continental shelf area of the South China Sea, with an average geothermal gradient in this area of approximately 3.4 °C/100 m, the sea bottom temperature is generally 4 °C, and the stratum temperature 800 m below the sea bottom meets the critical temperature condition of 31.1 °C. The average seawater density in the offshore area is 1020–1030 kg/m³, the hydrostatic pressure gradient is 0.99–1.01 MPa/100 m, and the formation pressure 800 m below the sea floor meets the conditions of 7.38 MPa supercritical pressure [58]. The simulation results showed that when the buried depth of the Beibu Gulf Basin is 800 m, the formation temperature is 32.5 °C, the pressure is 7.52 MPa, and thus the temperature and pressure conditions for CO₂ geological storage were determined (Figures 7 and 8). This shows that the modern underground pressure field in the Beibu Gulf Basin belongs to the normal pressure system, and the temperature field belongs to a medium-low temperature system. The CO₂ stored in the carbon reservoir of the Beibu Gulf Basin is in a supercritical state ($T > 31.1$ °C;

$p > 7.38$ MPa), which provides suitable temperature and pressure conditions for effective CO₂ injection and storage.

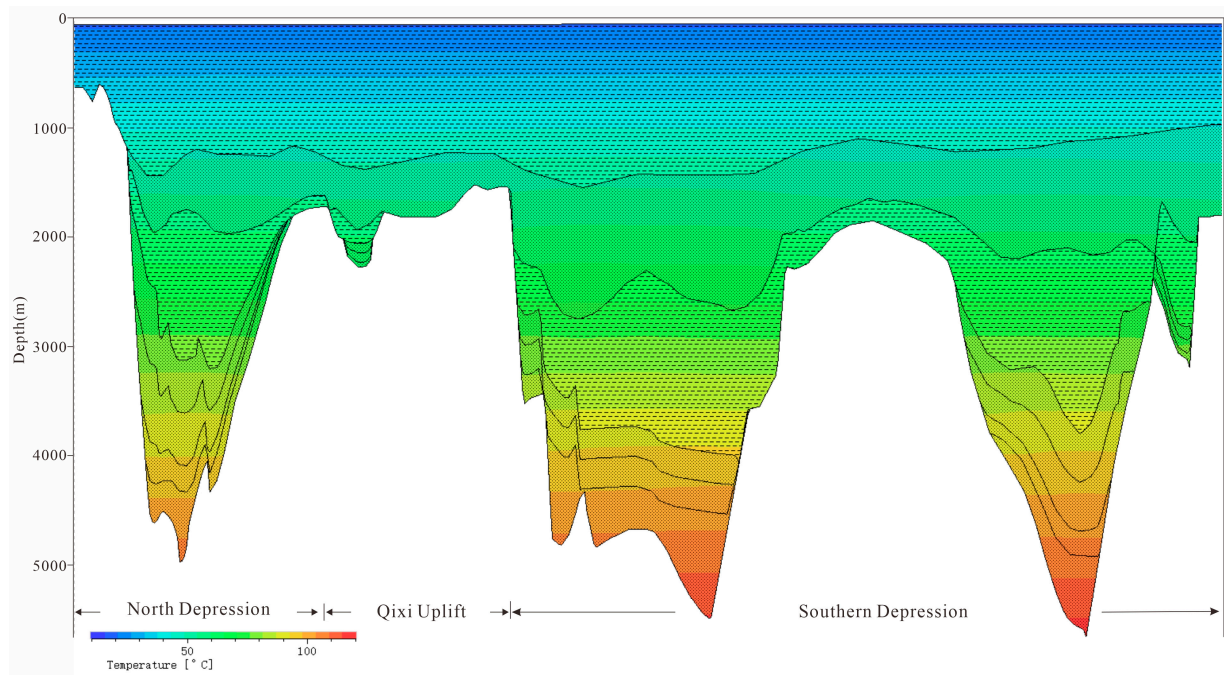


Figure 7. NW-SE stratigraphic temperature profile of the Beibu Gulf Basin (see Figure 1 for profile location).

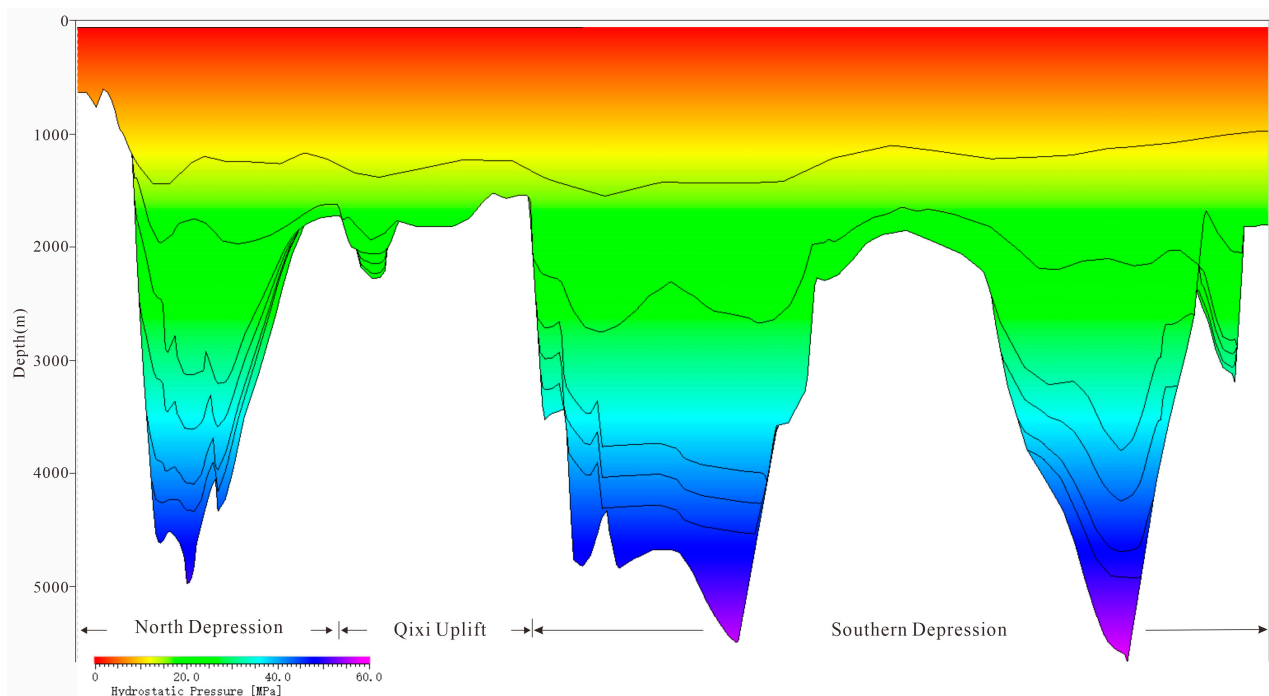


Figure 8. NW-SE formation pressure profile of the Beibu Gulf Basin (see Figure 1 for profile location).

5.4. Distance from the CO₂ Source

The distance from the CO₂ capture device determines the cost of implementation of the CCS project. Being too far away will increase the transportation cost, which is not conducive to the development of CO₂ geological storage projects. Therefore, the area close to the CO₂ source will be selected as much as possible to implement geological CO₂ storage. The provinces of Guangdong, Guangxi, and Hainan have developed industries, with high-emission heavy chemical industries accounting for a large proportion. For example, the scale of carbon emissions in western Guangdong (Zhanmaoyang) is approximately 70 million tons of CO₂ per year, making it the second largest CCUS cluster in Guangdong Province. The CO₂ storage capacity is limited due to the small scale, shallow burial, and lack of carbon burial conditions of continental sedimentary basins in South China. In such cases, the CO₂ storage potential of offshore basins is more important to surrounding economic areas. Compared with the Pearl River Mouth Basin, the Beibu Gulf Basin is closer to the coastal industrial zone, with obvious advantages in terms of source and sink, which belong to near-source carbon burial. Although the oil fields in the Beibu Gulf Basin are generally small in scale, low in reserves, and small in effective storage capacity, their deep saline aquifers can provide huge potential for CO₂ storage and have better conditions for CCUS-EOR and saltwater layer storage. The storage potential of an underground saline aquifer in Wushi Sag in the Beibu Gulf Basin is approximately 6.8 billion tons, that in Leidong Sag it is approximately 4.2 billion tons, and that in Weixinan Sag it is approximately 4.7 billion tons [28]. To obtain low-cost CO₂, the selection of storage sites should first consider areas close to modern coal chemical projects, where CO₂ capture units have been deployed.

5.5. Degree of Petroleum Exploration

When selecting favorable areas for CO₂ geological storage, sites with high degrees of exploration were selected to carry out CCS projects for economic considerations. By selecting areas with high degrees of exploration, we can fully use the existing exploration data to select the most suitable blocks for CO₂ geological storage and design a better construction plan. We can also fully use existing drilling, CO₂ transportation, and injection infrastructure to reduce engineering costs.

The Beibu Gulf Basin is primarily composed of seven sags, namely, Weixinan, Wushi, Maichen, Haizhong, Leidong, Fushan, and Haitoubei. The oil and gas exploration activities in this area have been concentrated in the Weixinan Sag and some blocks of the Wushi sag for numerous years. However, the degree of oil and gas exploration and geological research in Maichen, Haizhong Sag, and most areas of the Wushi Sag are low, with only some exploration wells and no commercial oil and gas discoveries (Figure 9). In recent years, rapid progress has been made in oil and gas exploration and geological research in the Fushan sag. Although the PetroChina Southern Oil and Gas Exploration Company has found small- and medium-sized oil and gas fields in this area and built an oil and gas production capacity with an annual output of 300,000 tons of oil equivalent, the overall level of oil and gas exploration and production is still low. Leidong Sag has been discovered and implemented as a sag for oil and gas exploration by CNOOC in recent years. Some exploration wells have been drilled; however, no breakthroughs have been made in oil and gas exploration. Although over 10 small- and medium-sized oil fields and multiple oil and gas structures have been found in the Weixinan, Wushi, and Fushan sags in the Beibu Gulf Basin, and good oil and gas shows have also been found in the Maichen Sag and other areas with a low degree of oil and gas exploration, the overall degree of oil and gas exploration and production in the basin is still low. Except for some blocks in the Weixinan, Wushi, and Fushan sags with a relatively high degree of oil and gas exploration and production, the remaining sags are still in the early stages of regional geological evaluation in oil and gas exploration.

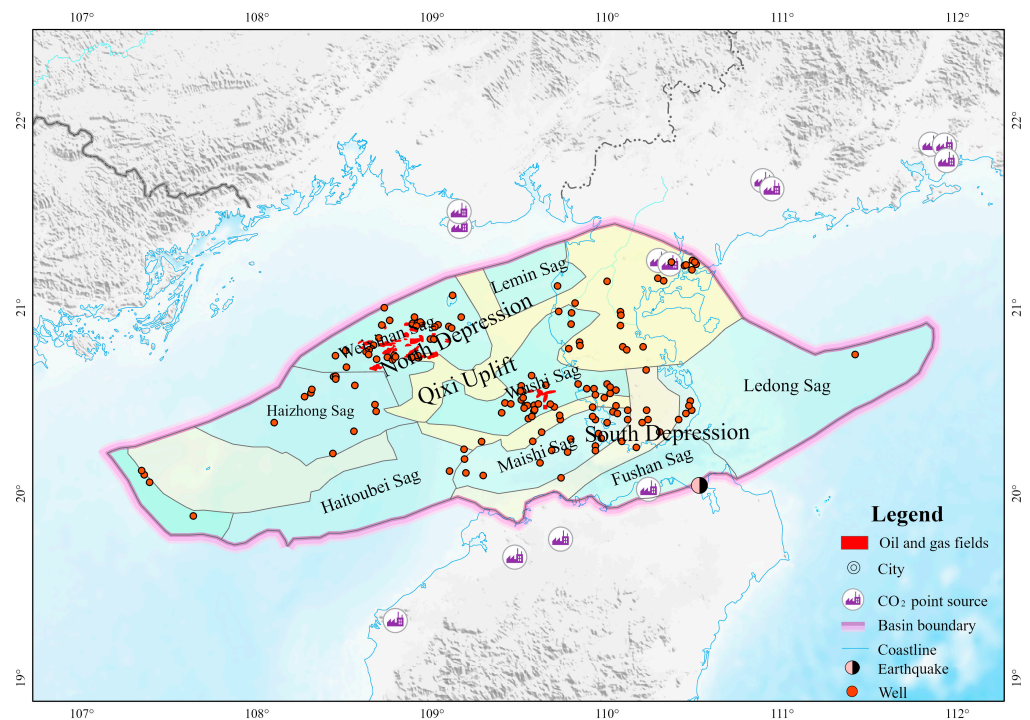


Figure 9. Petroleum exploration conditions of the Beibu Gulf Basin.

6. Conclusions

(1) Based on the requirements of the deep saline aquifer CO₂ storage project considering geological conditions and three aspects of the prerequisites for storage, significance of storage, and stability of carbon dioxide in the storage state, four first-level indicators, namely geological conditions, storage potential, hydrogeological conditions, and engineering conditions, were considered. Nineteen second-level indicators, including structural characteristics, faults, reservoir thickness, and formation water types, were selected as the index system for the suitability evaluation of carbon dioxide geological storage in the Beibu Gulf Basin.

(2) The suitability of CO₂ geological storage in deep saline aquifers of the Beibu Gulf Basin was quantitatively evaluated using an analytic hierarchy process and fuzzy synthetic evaluation method. The results showed that the suitability of geological storage in this area was Grade I, and the membership degrees were (0.84, 0.09, 0.06, and 0.01), indicating that the Beibu Gulf Basin is suitable for CO₂ geological storage. Considering the technical and economic considerations of CO₂ geological storage, it is necessary to optimize the target area of CO₂ geological storage in areas with a suitable burial depth of strata, superior reservoir conditions, close distance to CO₂ gathering devices, and a high degree of exploration to provide a scientific basis for the selection of CO₂ storage sites and the construction of geological storage projects. Further optimization of the evaluation index system will be the future research direction, which may be beneficial to improving the suitability evaluation for CO₂ geological storage in deep saline aquifers.

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Data Availability Statement: All the data and materials used in this study are available from the corresponding authors upon request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. A-B Judgment Matrix and Consistency Test.

A	B1	B2	B3	B4	$W_{B(n=1-4)}$
B1	1	1	1	1	0.25
B2	1	1	1	1	0.25
B3	1	1	1	1	0.25
B4	1	1	1	1	0.25
Rmax = 4 CI = 0 RI = 0.9 CR = 0 < 0.1					

Table A2. B1-C_{i(i=1-8)} Judgment Matrix and Consistency Test.

B1	C1	C2	C3	C4	C5	C6	C7	C8	$W_{C(i=1-8)}$
C1	1	3	3	1	6	1	1	3	0.1915
C2	1/3	1	1	1/3	2	1/3	1/3	1	0.0639
C3	1/3	1	1	1/3	2	1/3	1/3	1	0.0639
C4	1	3	3	1	5	1	1	3	0.1875
C5	1/6	1/2	1/2	1/5	1	1/6	1/6	1/2	0.0327
C6	1	3	3	1	6	1	2	4	0.2212
C7	1	3	3	1	6	1/2	1	3	0.1778
C8	1/3	1	1	1/3	2	1/4	1/3	1	0.0615
Rmax = 8.0507 CI = 0.0072 RI = 1.41 CR = 0.0051 < 0.1									

Table A3. B2-C_{i(i=9-13)} Judgment Matrix and Consistency Test.

B2	C9	C10	C11	C12	C13	$W_{C(i=9-13)}$
C9	1	3	1	6	1	0.2951
C10	1/3	1	1/3	3	1/2	0.1169
C11	1	3	1	5	1	0.2850
C12	1/6	1/3	1/5	1	1/4	0.0514
C13	1	2	1	4	1	0.2517
Rmax = 5.0503 CI = 0.0126 RI = 1.12 CR = 0.0113 < 0.1						

Table A4. B3-C_{i(i=14-16)} Judgment Matrix and Consistency Test.

B3	C14	C15	C16	$W_{C(i=14-16)}$
C14	1	3	2	0.5396
C15	1/3	1	1/2	0.1634
C16	1/2	2	1	0.2969
Rmax = 3.0092 CI = 0.0046 RI = 0.58 CR = 0.0079 < 0.1				

Table A5. B4-C_{i(i=17-19)} Judgment Matrix and Consistency Test.

B4	C17	C18	C19	$W_{C(i=17-19)}$
C17	1	3	5	0.6483
C18	1/3	1	2	0.2297
C19	1/5	1/2	1	0.1220
Rmax = 3.0037 CI = 0.0019 RI = 0.58 CR = 0.0033 < 0.1				

Table A6. Evaluation results of each index.

First Level	Second Level	Quantized Value	Membership
Geological conditions B1	Tectonic characteristics C1	1	(1, 0, 0, 0)
	Fault C2	0.5	(0, 0.5, 0.5, 0)
	Geothermal gradient C3	1	(1, 0, 0, 0)
	Heat flow C4	1	(1, 0, 0, 0)
	Formation temperature C5	1	(1, 0, 0, 0)
	Seal condition C6	1	(1, 0, 0, 0)
	Earthquake C7	0.5	(0, 0.5, 0.5, 0)
	Volcano C8	0.2	(0, 0, 0.3, 0.7)
Storage potential B2	Area C9	1	(1, 0, 0, 0)
	Reservoir thickness C10	0.8	(0.7, 0.3, 0, 0)
	Reservoir buried depth C11	1	(1, 0, 0, 0)
	Reservoir physical property C12	0.4	(0, 0.1, 0.9, 0)
	Reservoir pressure C13	1	(1, 0, 0, 0)
Hydrogeological conditions B3	Reservoir water type C14	1	(1, 0, 0, 0)
	Mineralization C15	0.8	(0.7, 0.3, 0, 0)
	Hydrodynamics C16	0.9	(1, 0, 0, 0)
Engineering conditions B4	Exploration and development degree C17	1	(1, 0, 0, 0)
	Offshore distance C18	0.8	(0.7, 0.3, 0, 0)
	Sea depth C19	0.5	(0, 0.5, 0.5, 0)

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