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Research on Evaluation of the Carbon Dioxide Sequestration Potential in Saline Aquifers in the Qiongdongnan–Yinggehai Basin

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Abstract: This paper evaluates the carbon dioxide sequestration potential in the saline aquifers of the South Qiongdongnan–Yinggehai Basin. By using a hierarchical evaluation method, the assessment is divided into five stages: the basin level, the zone level, the target level, the site level, and the injection level. The study primarily focuses on evaluating the sequestration potential of and identifying favorable zones of saline aquifers at the basin and zone levels. The optimized volumetric method is adopted, based on the integration of multi-source data such as regional geological maps, seismic data, core porosity, and permeability. The results show that the estimated potential of the Yinggehai Basin is 60.6 billion tons at the basin level and 54.6 billion tons at the zone level. Additionally, the estimated potential of the South Qiongdongnan Basin is 261.5 billion tons at the basin level and 234.8 billion tons at the zone level. The suitability evaluation indicates that the Yinggehai Basin is moderately suitable overall, the northern depression of the South Qiongdongnan Basin is suitable, the central uplift is moderately suitable, and the central depression is not suitable. This study provides a scientific foundation for carbon dioxide sequestration in marine basins and introduces novel ideas and methods for future similar research. This is highly significant for subsequent engineering applications and decision-making processes.

Keywords: carbon dioxide sequestration; saline aquifer potential evaluation; volumetric method; Qiongdongnan Basin; Yinggehai Basin; suitability evaluation

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1. Introduction

With the increasingly severe issue of global climate change, reducing greenhouse gas emissions has become a common goal of the international community. Carbon dioxide (CO_2), as one of the primary greenhouse gases, plays a crucial role in combating climate change by reducing emissions [1]. Among various emission reduction technologies, Carbon Capture, Utilization, and Storage (CCUS) technology has attracted widespread attention due to its potential for large-scale emission reduction.

CO_2 sequestration technology is mainly divided into three types: ocean storage, geological storage, and mineral carbonation [2]. Ocean storage mainly involves injecting CO_2 into the ocean water column or submarine sediments [3]. Geological storage utilizes underground geological structures such as depleted oil and gas reservoirs, saline aquifers, and coal seams for sequestration [4]. Mineral carbonation permanently stores CO_2 by transforming it into carbonate minerals [5]. Each one of these technologies has unique characteristics in terms of safety, cost-effectiveness, and storage capacity. They require a comprehensive assessment based on the specific geological conditions and environmental impacts.

Geological sequestration of CO_2 involves injecting captured CO_2 into underground geological formations for long-term or permanent isolation. Among them, saline aquifers have become an important target reservoir for CO_2 geological sequestration [6,7] due to their widespread distribution, large storage potential, and relatively low storage risk.

Globally, CO_2 sequestration projects are mainly concentrated in North America and Europe, such as the Sleipner and Weyburn projects [8,9]. China is also actively promoting CCUS technology, especially in the field of saline aquifer sequestration [10,11]. At present, there are over 20 commercial-scale CCUS projects in operation worldwide [12]. These projects cover the entire chain, from capturing CO_2 from power and industrial emission sources to utilizing and storing it through enhanced oil recovery (EOR) and deep geological storage technologies. Despite progress, the global deployment of CCUS technology is still in its early stages, facing challenges in terms of technological maturity, cost-effectiveness, policy support, and leakages (affecting environmental impact) that are related to the aquifer properties.

The South Qiongdongnan–Yinggehai Basin, situated in the northern part of the South China Sea, is a sedimentary basin of strategic significance. Its saline aquifers are considered potential sites for CO_2 sequestration [11,13]. This paper evaluates it separately as the Yinggehai Basin and the Qiongdongnan Basin. However, to achieve effective CO_2 sequestration, it is first necessary to accurately evaluate the sequestration potential. This paper aims to evaluate the CO_2 sequestration potential in the saline aquifers of the Yinggehai–Qiongdongnan Basin to provide a scientific basis and technical support for CO_2 sequestration in the area.

In order to conduct the evaluation of sequestration potential in an organized and efficient manner, this paper first defines the scope and corresponding levels of the evaluation. Referring to global exploration and development processes and the standards of organizations such as the Carbon Sequestration Leadership Forum (CSLF), the United States Department of Energy (US DOE), and the Society of Petroleum Engineers (SPE) [14–20], this paper innovatively proposes a structured evaluation framework. It forms a level division scheme for the evaluation of the sequestration potential of saline aquifers in the Yinggehai–Qiongdongnan Basin. This scheme divides the evaluation of sequestration potential into five stages: the basin level, the zone level, the target level, the site level, and the injection level. These stages correspond to predicted potential, presumed potential, controlled potential, basic reserves, and engineering reserves, respectively [21].

In its selection of an evaluation method, this paper adopts the optimized volumetric method as the primary calculation method for assessing sequestration potential. The fundamental principle of the volumetric method is to assess all the pore space in the geological body that can be utilized for CO_2 sequestration and then convert these volumes into the corresponding CO_2 sequestration potential. The optimized volumetric method is suitable for evaluating the sequestration potential at the large-scale basin and zone levels. It involves relatively simple parameter selection and easy operation.

In the specific calculation process for carbon sequestration potential, this paper has conducted research on the precise acquisition and processing of key parameters. The required key parameters are described in detail, including the area of the basin or zone, effective sandstone thickness, stratigraphic thickness, sandstone-to-shale ratio, average porosity, CO_2 density, and sequestration efficiency factor. Precise acquisition of these parameters is crucial for accurate assessment of the sequestration potential. Therefore, this paper has collected regional geological maps, seismic data, core porosity, and permeability data. It utilized ArcGIS 10.2 software and the geological modeling software GXplorer V5.8 for data preparation, structural modeling, reservoir facies modeling, and attribute modeling to establish a sequestration potential evaluation model. This model fully considers geological structures, sedimentary characteristics, and CO_2 sequestration conditions, thereby enhancing the reliability of the evaluation results.

Ultimately, this paper conducted a quantitative calculation of the CO_2 sequestration potential in the saline aquifers of the Yinggehai–Qiongdongnan Basin and performed a suitability evaluation that integrated geological conditions, engineering conditions, and socio-economic factors. The evaluation results not only provide significant decision support

for CO_2 sequestration in the region but also serve as a reference for sequestration potential evaluations in other similar basins. Through this study, we aim to contribute to the advancement of global CCUS technology and the mitigation of climate change.

2. Evaluation Method for Carbon Sequestration Potential in Saline Aquifers

2.1. Division of Evaluation Levels at Present

Currently, the assessment of saline aquifer sequestration potential in various countries typically involves a tiered evaluation method. Different assessment methods and parameters are utilized to evaluate the carbon sequestration potential at different levels. This paper categorizes the evaluation of the carbon sequestration potential of the saline aquifers in the Yinggehai–Qiongdongnan Basin into five stages. The corresponding types of sequestration potential are predictive potential, presumed potential, controlled potential, basic reserves, and engineering reserves, as shown in Figure 1.

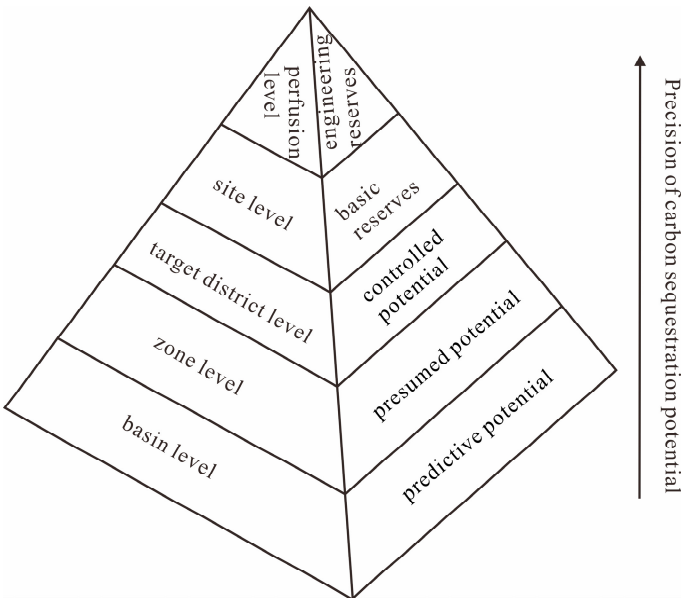

Figure 1. Hierarchical scheme for evaluating the sequestration potential of saline aquifers.

This paper primarily conducts basin-level and zone-level evaluations of the sequestration potential in the Yinggehai–Qiongdongnan Basin. The aim is to determine the predicted capacity for CO_2 sequestration in saline aquifers and the presumed potential in favorable zones of the Yinggehai–Qiongdongnan Basin. The basin-level evaluation focuses on the entire Yinggehai–Qiongdongnan Basin, analyzing the projected potential of CO_2 sequestration in the saline aquifers. This assessment is based on the compilation and analysis of regional marine geological surveys and data from oil and gas resource censuses. The zone-level evaluation focuses on first-order tectonic units within the basin, obtaining relevant data on stratigraphy, sedimentation, structure, and geothermal conditions from oil and gas geological surveys. Through comprehensive geological research, this study assesses the potential for CO_2 sequestration in saline aquifers located in different depressions and uplifts within the basin.

2.2. Calculation Methods

(1) Main Calculation Methods for Sequestration Potential

Currently, there are six main methods for calculating the geological sequestration potential of carbon dioxide. These methods can be broadly categorized into two groups: mechanism-based methods and volumetric methods (refer to Table 1) [19–23]. The fundamental principle of the volumetric method is to calculate all the pore space in the geological body that is available for CO_2 sequestration and then convert this volume into

the corresponding CO_2 sequestration potential under the specified storage conditions. The mechanism-based method's basic principle is that after CO_2 injection, it is captured by different mechanisms and stored in various locations. This method calculates the CO_2 sequestration potential under different storage mechanisms to determine the total sequestration potential of the evaluated geological body. Among the six calculation methods, three are applicable to basin-level and zone-level potential calculations: the volumetric method from the U.S. Department of Energy Geological Working Group, the method from the Carbon Sequestration Leadership Forum Geological Working Group, and the calculation method from the U.S. Geological Survey.

Table 1. Summary of estimation methods for global major carbon dioxide storage potential.

Evaluation Level	Applicable Conditions	Estimation Method
E	Basin level	Mechanism Method (Forum Geological Work Group) [22] Volumetric Method (U.S. Department of Energy Geological Task Force; U.S. Geological Survey) [19]
D	Zone level	Mechanism Method (Forum Geological Work Group) Volumetric Method (U.S. Department of Energy Geological Task Force; U.S. Geological Survey)
C	Target district level	Mechanism Method (Forum Geological Work Group) Volumetric Method (U.S. Department of Energy Geological Task Force; U.S. Geological Survey)
B	Site level	Mechanism Method (Forum Geological Work Group) [23,24]
A	Perfusion level	Mechanism Method

The calculation method of the U.S. Geological Survey requires relatively high standards for the division of the assessment units within the basin and the physical property parameters of the storage formation. The parameters obtained in the study area are limited, which makes it impossible to use the mechanism method for potential evaluation. The accuracy of the sequestration potential calculation in practice is directly related to the precision and understanding of the actual data of the storage unit [25]. This method is not utilized in this study to estimate the carbon dioxide sequestration potential at the basin and zone levels. The assumptions recommended by the Forum Geological Working Group and the U.S. Department of Energy Geological Working Group are consistent. In principle, calculation of the bound gas sequestration potential and the volumetric method calculation are mathematically consistent [22]. In this study, in estimating the potential for marine carbon sequestration at the zone level, dissolution sequestration and mineral sequestration are temporarily excluded. The volumetric method is employed to estimate the carbon dioxide sequestration potential in the primary sedimentary basins of China's marine regions. Although dissolution sequestration and mineral sequestration are important for a comprehensive discussion of the carbon sequestration potential in the region, these two methods fall under the category that must be considered using the mechanism method, and relevant parameters for evaluation could not be obtained in this study. Therefore, the calculation of these two sequestration amounts will not be considered temporarily in this study.

(2) Selection of Sequestration Potential Evaluation Methods

The evaluations of the saline aquifer basin-level and zone-level sequestration potential in the Yinggehai–Qiongdongnan Basin both utilize the volumetric method. This method is suitable for large-scale basin-level and zone-level sequestration potential evaluations, while the mechanism-based method is applicable to target-level and site-level sequestration potential assessments. The volumetric method involves relatively simple parameter selection, whereas the mechanism-based method calculates the CO_2 sequestration potential for different storage mechanisms after CO_2 injection into the saline aquifer. These mechanisms include structural stratigraphic storage, residual storage, dissolution storage, mineral storage, and hydrodynamic storage. The total sequestration potential is obtained by summing these individual potentials. Due to the challenges in acquiring all the required evaluation parameters for the

mechanism-based method during the evaluation of sequestration potential at the basin and zone levels, this assessment does not employ the mechanism-based method.

For evaluation of the basin-level sequestration potential, the Yinggehai–Qiongdongnan Basin is considered the evaluation unit, and the primary storage and cap rock formations developed during each geological period within the basin are summarized. The potential evaluation parameters obtained from several exploratory wells at various locations within the basin are utilized to predict the sequestration potential of the saline aquifers throughout the entire basin. The data required for basin-level potential evaluation include regional geological maps, regional structural models, fault distribution maps, topographic maps, 2D seismic data, core porosity and permeability data, sedimentary facies, etc. These data are primarily sourced from 1:1 million regional geological survey results and publicly available offshore oil data.

For zone-level sequestration potential evaluation, depressions and uplifts within the basin are considered the evaluation units. The storage and cap rock formations formed during each geological period are then further detailed and generalized. Data collection within the unit, including drilling, seismic geophysics, reservoir, and fluid data, enriches the calculation parameters for the carbon sequestration potential and allows for calculation of the sequestration potential for each zone. The data required for zone-level potential evaluation include regional geological maps, 2D seismic data, core porosity and permeability data, regional structural models, local geological maps, structural contour maps, reservoir geometry maps, sedimentary facies data, capillary pressure data, pore pressure tests, and pore fluid properties.

In the basin-level evaluation, the potential for CO_2 geological sequestration is assessed with the basin as the focal point. The estimation parameters are broadly generalized, including porosity and the sandstone-to-shale ratio, which can be based on the average values across the entire evaluation area of the basin for calculation. In contrast, the zone-level evaluation considers the depressions and uplifts within the basin the evaluation objects, and the potential estimation parameters are selected based on the actual data collected from these subsea geomorphological forms. The calculation formula is as follows [26]:

$$P = A \times h \times \varphi \times \rho_{CO_2} \times E \quad (1)$$

$$h = H \times R \quad (2)$$

where:

P represents the CO_2 sequestration potential in tonnes.

A represents the area of the basin or zone, measured in square meters (m^2).

H represents the total sandstone thickness of the basin or zone, measured in meters.

R represents the sandstone-to-shale ratio of the basin or zone. It is calculated as the ratio of the sandstone thickness (effective thickness) for CO_2 sequestration in the target evaluation area to the thickness of the evaluation stratum, expressed as a percentage.

φ represents the average porosity of the sandstone in the basin or zone, measured as a unit fraction.

ρ_{CO_2} represents the density of CO_2 under sequestration conditions, which is approximated as an average value every 200 m instead of the true value. This approximation assumes that the CO_2 density remains consistent within a 200 m thickness range and is calculated based on the stratum's temperature and pressure, measured in tonnes/m^3.

E represents the effective coefficient for CO_2 sequestration, which reflects the proportion of the pore space volume occupied by CO_2, measured as a fraction of 1. Funded by the International Energy Agency's greenhouse gas project [27], a CO_2 sequestration model is established based on parameters from over 20,000 oil and gas reservoirs worldwide [28]. The research involves simulating mathematical scenarios at a specific injection rate (up to 1 million tons per year) to determine the effective plane, sandstone layer thickness, porosity, volume, and microscopic replacement efficiency. Subsequently, Monte Carlo sampling simulation [29] was used to calculate the effective coefficients for sealing saltwater layers

dominated by clastic rocks, dolomite, and limestone. Within a confidence interval of 10% to 90%, the effective coefficients are 1.2% to 4.1%, 2.0% to 3.6%, and 1.3% to 2.8%, respectively. At a confidence level of 50%, they are 2.4%, 2.7%, and 2.0%, respectively.

3. Calculation Model and Parameter Selection

3.1. Sequestration Potential Calculation Model

Based on the geological structure of the basin and zone, this study establishes a stratigraphic volume model for evaluating the potential for CO_2 sequestration (see Figure 2) and a model for calculating the sand-to-shale ratio controlled by facies (see Figure 3). The stratigraphic volume model divides the sedimentary strata from 800 to 3200 m in depth into n calculation units from top to bottom at a certain interval h. Each calculation unit has a different areal distribution of strata, geological body volume, sandstone porosity, and CO_2 density. This model serves as a constraint. During potential evaluation, the parameters of each calculation unit are obtained separately to describe the spatial heterogeneity of each parameter, thereby enhancing the accuracy of potential evaluation.

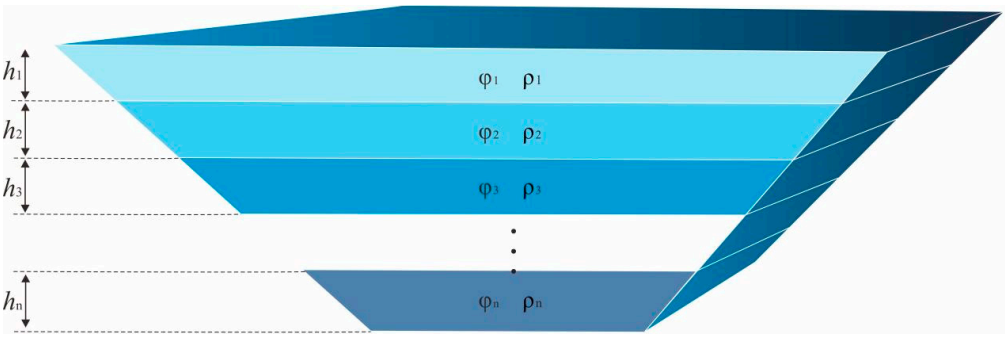

Figure 2. Stratigraphic volume model. φ represents the porosity of sandstone; ρ represents the density of CO_2; h represents the thickness of the calculation unit.

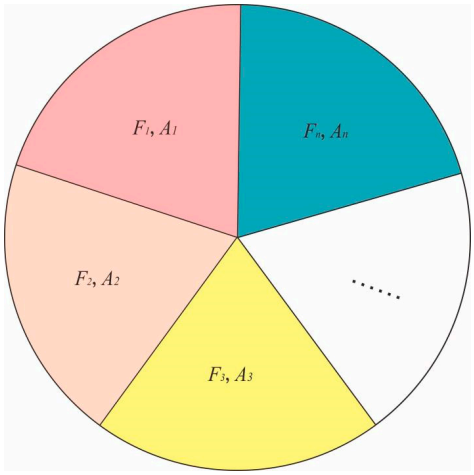

Figure 3. Facies-controlled sand-to-shale ratio calculation model.

The sand-to-shale ratio of the stratum is a key parameter in the evaluation of its potential. Drilling data from marine areas show that various sedimentary facies belts exhibit different sand-to-shale ratio values. In this evaluation, a calculation model is established for various types of sedimentary facies and their sand-to-shale ratios, taking into account the sedimentary facies plan of the basin and the zone as a constraint. This model considers the weight in the evaluation unit. The weight value is obtained through drilling data calculation, as illustrated in Figure 3. In the model, various colors represent distinct sedimentary facies types. *Fn* denotes the percentage of sandstone thickness drilled in each sedimentary facies belt, while *An* represents the area of each facies belt.

3.2. Parameter Acquisition and Processing Methods

Volume (A × h): In this study, regional geological data and literature were collected to establish a map of the sediment thickness of the Cenozoic era using ArcGIS software. The software was then used to directly calculate the volume of the evaluation area (ranging from 800 to 3200 m, with each 200 m stratum divided into layers and calculated separately).

Saline aquifer coarse sandstone thickness (h) refers to the approximate total sandstone thickness within the evaluated total thickness. The sandstone layer thickness is obtained by multiplying the total thickness by the sand-to-shale ratio (R) of the area (R = sandstone layer thickness (h)/evaluated total thickness (H)). The sand-to-shale ratio (R) used in estimating the CO_2 sequestration potential for basins and zones refers to the representative sedimentary facies of the basin or zone. The sandstone content of each facies is restricted and then calculated through weighted averaging of the areas of each sedimentary facies. For some basins that lack sufficient sedimentary facies sand-to-shale ratio data, the sand-to-shale ratio value is obtained through appropriate correction referring to data from geologically similar basins.

Porosity (φ): The porosity of the strata changes vertically due to the effects of vertical compaction and dissolution. Therefore, this study utilizes the compaction curves of each basin to determine porosities at various depths for calculation.

CO_2 Density (ρ): When calculating the effective sequestration potential of CO_2 in saline aquifers and oil and gas reservoirs, the density of CO_2 is determined based on its actual stratigraphic position. This calculation is performed using the Peace software (https://www.peacesoftware.de/einigewerte/co2_e.html, accessed on 10 June 2024). Some CO_2 densities calculated by the Peace software are corrected using the data table from the "Carbon Dioxide Thermodynamic Properties Handbook" [30]. The temperature and pressure at the stratigraphic position are determined by calculating the seafloor temperature and depth, as well as the corresponding geothermal gradient and pressure gradient. At the same time, we conducted a sensitivity analysis to assess the influence of variations in the carbon dioxide density data on the evaluation results, ensuring the robustness of our conclusions against these potential errors.

3.3. Calculation of the Sequestration Potential

Based on a comprehensive collection of key parameters such as the division of tectonic units in each basin, the thickness of Cenozoic strata, storage and cap rock combinations, geothermal geological conditions, the distribution of the main storage strata sedimentary facies, and porosity, the volumetric method is used to calculate the sequestration potential at the basin and zone levels.

Firstly, focusing on a basin or zone as the research object, a saline aquifer sequestration potential evaluation model is constructed using the principle of facies-controlled modeling. The geological modeling software GXplorer and the geographic information software ArcGIS are utilized for this purpose. The basic process includes data preparation, structural modeling, reservoir facies modeling, and reservoir attribute modeling, and the established model is gridded.

Secondly, within the established model, the density of CO_2 is calculated based on factors such as seawater depth, seafloor temperature, geothermal gradient, stratigraphic depth, and stratigraphic pressure coefficient. Subsequently, an isopach map of CO_2 density is created.

Then, based on the thickness map of the reservoir, the area of each layer can be calculated individually. This helps determine the effective reservoir area, enabling the calculation of the reservoir volume layer by layer.

Finally, by combining the thickness and porosity isopach maps of the reservoir, the predicted potential and the presumed potential of saline aquifer sequestration for each research object are calculated separately, and the results are aggregated.

4. Saline Aquifer Carbon Sequestration Suitability Evaluation

A suitability evaluation for geological carbon sequestration aims to assess and select appropriate sites using a series of geological, engineering, socio-economic, and other conditions, which provide a scientific basis for subsequent engineering and decision-making tasks [31,32]. These indicators need to comprehensively consider geological conditions such as the distribution of marine basin reservoirs and temperature–pressure field characteristics, as well as engineering implementation conditions, including water depth, offshore distance, the extent of oil and gas exploration and development, etc. This study established an indicator system consisting of necessary and key indicators to evaluate the geological suitability for carbon dioxide sequestration in marine basins and zones.

4.1. Necessary Indicators

The necessary indicators represent the quality of the basic geological conditions for geological CO_2 sequestration. The necessary indicators consist of three first-level indicators, sequestration potential, geological conditions, and engineering conditions, which include 11 s-level indicators at the basin level and 13 at the zone level (Table 2).

The determination of weights for the first-level and second-level necessary indicators is based on the following steps: First, researching the weight value range of global indicators for the suitability evaluation for marine CO_2 geological sequestration [27,33–37]; second, determining the weights of each first-level and second-level indicator based on the actual data and the specific conditions of China's marine sedimentary basins. In this evaluation, we integrate the weights from the two sources mentioned above and reanalyze and calculate them using the AHP to ultimately determine the weights of each first-level and second-level indicator.

In the basin-level suitability evaluation indicator system, the weight of the first-level indicator of sequestration potential is 0.3. The weights of the four second-level indicators, namely area, Cenozoic stratigraphic thickness, basin predicted potential, and predicted potential per unit area, are 0.05, 0.05, 0.1, and 0.1, respectively (Table 2). The total weight of the first-level indicator of geological conditions is 0.3. The weights of the four second-level indicators—exploration degree, maximum magnitude of seismic activity in the past century, seafloor temperature, and geothermal gradient—are 0.1, 0.1, 0.05, and 0.05, respectively. The weight of the first-level indicator for engineering conditions is 0.4. The weights of the three second-level indicators—development degree, offshore distance, and seawater depth—are 0.1, 0.1, and 0.2, respectively. The distance from the shore and the depth of seawater directly affect the project cost. These are critical factors to consider when selecting construction platforms, drilling techniques, and transportation methods for marine CO_2 geological sequestration.

Table 2. Indicator system for the suitability evaluation of CO_2 geological sequestration in the Yinggehai–Qiongdongnan Basin and zones.

Indicator Level	First-Level Indicators (Basin Weight/Zone Weight)	Second-Level Indicators (Basin Indicator Weight)	Second-Level Indicators (Zone Indicator Weight)	Description
Necessary Indicators	Sequestration Potential (0.3/0.4)	Basin Area (0.05)	Zone Area (0.1)	The area of the basin/zone projected onto the plane.
		Basin Thickness (0.05)	Zone Thickness (0.1)	The thickness of Cenozoic strata buried between 800 and 3200 m in the basin/zone. The thicker the strata, the more favorable it is for CO_2 geological sequestration. The burial depth also affects the implementation conditions.
		Sequestration Potential (0.1)	Sequestration Potential (0.1)	The predicted or presumed potential of the basin/zone for CO_2 geological sequestration. The greater the sequestration potential, the more suitable it is for CO_2 geological sequestration.
		Per Unit Area Sequestration Potential (0.1)	Per Unit Area Sequestration Potential (0.1)	The potential amount of CO_2 that can be sequestered per unit area in the basin/zone.

Table 2. *Cont.*

Indicator Level	First-Level Indicators (Basin Weight/Zone Weight)	Second-Level Indicators (Basin Indicator Weight)	Second-Level Indicators (Zone Indicator Weight)	Description
Necessary Indicators	Geological Conditions(0.3/0.3)	Exploration Degree (0.1)	Exploration Degree (0.05)	This reflects the level of knowledge and data richness of the sedimentary basin/zone. The higher the degree of exploration, the more reliable and accurate the evaluation indicators become. This is beneficial for accurately assessing the suitability of CO_2 geological sequestration in the sedimentary basin/zone.
		Seafloor Temperature (0.05)	Seafloor Temperature (0.05)	The average temperature of seawater at the seabed. The temperature of seawater has a certain impact on geothermal energy. For a marine region, the temperature of the seafloor primarily depends on the latitude and water depth, and the average value over multiple years is considered.
		Geothermal Gradient (0.05)	Geothermal Gradient (0.05)	Expressed as the number of degrees Celsius (°C) of temperature increase per 100 m of vertical depth. This indicator reflects the rate of temperature increase within the strata with depth and is one of the important parameters that affect the potential of CO_2 geological sequestration. The geothermal gradient is determined by the Earth's internal heat and the thermal conductivity of the strata.
		Fault activity (0.1)	Fault Activity (0.05)	Divided into three categories: inactive faults, faults without through-going faults, and faults with through-going faults.
			Reservoir Conditions (0.05)	Based on the size of porosity, the reservoir carbon layers are divided into three categories: high-quality, good, and effective carbon storage layers.
			Cap Rock Conditions (0.05)	Cap rocks are classified based on their thickness and scale.
	Engineering Conditions (0.4/0.3)	Development Degree (0.1)	Development Degree (0.1)	This reflects the extent of oil and gas development in the basin/zone. The higher the level of development, the more advanced the drilling platforms and pipeline network become, leading to better engineering conditions.
		Offshore Distance (0.1)	Offshore Distance (0.1)	The shortest distance from the basin/zone to the coast. The farther the distance, the higher the transportation and injection costs, the greater the technical difficulty, and the less favorable it is for CO_2 geological sequestration.
		Seawater Depth (0.2)	Seawater Depth (0.1)	When the depth of seawater exceeds 150 m, more sophisticated and costly platforms and processes are necessary. The greater the depth, the higher the technical difficulty, and the greater the cost.
Key Indicators	Seismic Belt			Based on the occurrence of earthquakes above a magnitude of 8 in a basin or zone over the past century, it is divided into seismic belts. If the condition applies, a value of 0 is assigned; otherwise, a value of 1 is assigned.
	Drilling Engineering Feasibility			The feasibility of drilling engineering is primarily determined by whether oil and gas drilling projects have been implemented in the basin or zone. If there is no oil and gas drilling, this indicator is assigned a value of 0; otherwise, it is assigned a value of 1.

In the zone-level suitability evaluation indicator system, the weight of the first-level indicator of sequestration potential is 0.4. The weights of the four second-level indicators—namely area, thickness, potential, and richness (per unit area sequestration potential)—are each 0.1 (Table 2). The weight of the first-level indicator of geological conditions is 0.3, while the weights of the six second-level indicators—exploration degree, storage layer, cap rock, fault activity, seafloor temperature, and geothermal gradient—are each 0.05. The weight value of the first-level indicator for engineering conditions is 0.3, while the weights of the second-level indicators for development degree, offshore distance, and seawater depth are each 0.1.

4.2. Key Indicators

Key indicators are crucial for evaluating the safety and feasibility of drilling projects in offshore CO_2 geological storage. Whether the constraints of the key indicators are met determines the suitability of CO_2 geological storage in the marine area. This assessment is based on two indicators: whether it is located in a seismic belt and whether there is oil and gas drilling (Table 2).

5. Results of Carbon Sequestration Potential Evaluation in Saline Aquifers

5.1. Carbon Sequestration Potential and Suitability Evaluation of the Yinggehai Basin

(1) Geological Characteristics of Carbon Sequestration

The Yinggehai Basin is situated at the northern edge of the South China Sea, near Hainan Province, covering an area of approximately 11.5×10^4 km^2. The calculated area is 4.7×10^4 km^2, and the average water depth is approximately 50 m. The thickness of the Cenozoic strata ranges from 2070 to 18,000 m (Figure 4). Within the stratigraphic interval of an 800 to 3200 m depth, three sets of storage–cap rock combinations are mainly developed (Figure 5). Among these, the coastal and deltaic sandstone of the Sanya Formation are effective storage layers with an average porosity of 13.9%, and the overlying upper mudstone of the Sanya Formation serves as the cap rock. The coastal and deltaic sandstone of the Huangliu Formation and the turbiditic sandstone are good storage layers with porosities between 16% and 22%, and the overlying Yinggehai Formation mudstone serves as the cap rock. The deltaic and turbiditic sandstone of the Yinggehai Formation are high-quality storage layers with porosities between 20% and 30%, and the overlying upper mudstone of the Yinggehai Formation serves as the cap rock. The basin experiences weak seismic activity and exhibits good crustal stability.

The Yinggehai Basin straddles the maritime boundary between China and Vietnam. This evaluation only assesses the carbon sequestration potential within the national borders. The Yinggehai Basin has a shallow water depth, with a seafloor temperature of about 24 °C and a relatively high geothermal gradient ranging from 31 to 43 °C/km. The average geothermal gradient in the basin is 40 °C/km, 39 °C/km on the eastern slope, and 36 °C/km in the central depression (Table 3).

Table 3. Data table of geothermal gradient, seafloor temperature, and water depth for various zones in the Yinggehai Basin.

Basin and Zone	Geothermal Gradient (°C/km)	Seafloor Temperature (°C)	Water Depth (m)
Yinggehai Basin	40	24	50
Central Depression	36	24	50
Eastern Slope	39	24	50
Western Slope	39	24	50

The calculated CO_2 density for the Yinggehai Basin at depths of 800 to 3200 m ranges between 263 and 518 kg/m^3 (basin), 289 and 560 kg/m^3 (central depression), 269 and 528 kg/m^3 (eastern slope), and 269 and 528 kg/m^3 (western slope).

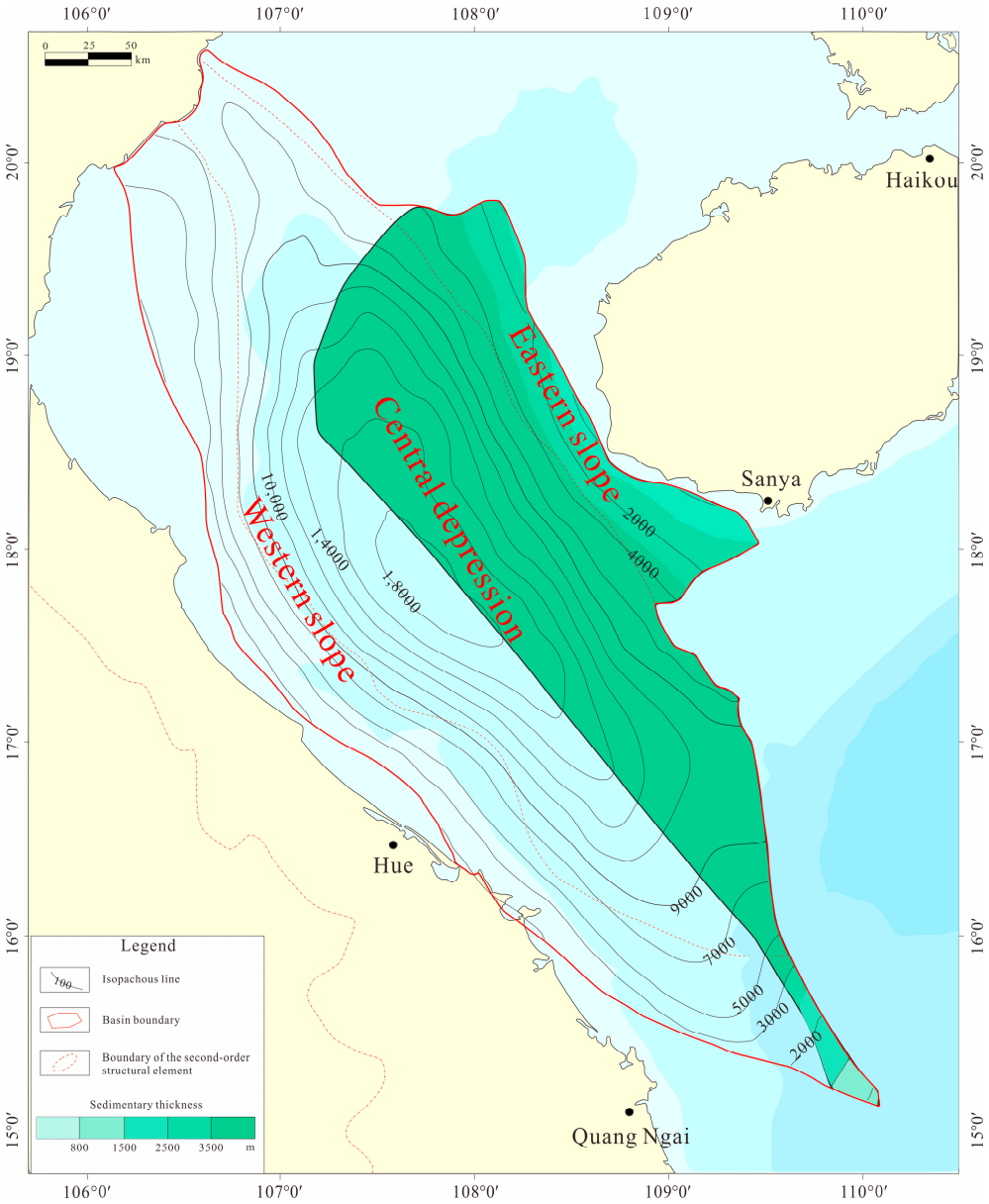

Figure 4. Map of Cenozoic thickness in the Yinggehai Basin.

(2) Results of Carbon Sequestration Potential and Suitability Evaluation

The results of the CO_2 geological sequestration potential and suitability evaluation for the Yinggehai Basin are shown in Table 5. The predicted potential of CO_2 geological sequestration at the basin level is 60.6 billion tons, and the estimated potential at the zone level is a total of 54.6 billion tons. When evaluating the CO_2 storage potential of the Ledong formation in the Yinggelai Basin, the storage potential of the formation may have been overestimated, with an estimated range of approximately 10%. This estimation is based on an understanding of the actual thickness of the formation. We will further discuss this potential overestimation and its impact on the overall evaluation in the conclusion section.

The basin has a high degree of oil and gas exploration and development [38,39], with some gas reservoirs in the production depletion stage. As of 2021, there are 160 wells in the basin, with a well-established oil and gas transportation network and comprehensive development engineering data. It has characteristics such as shallow water, proximity to surrounding industrial areas, a short transportation distance, large effective space, and mature engineering conditions. However, the high formation pressure coefficient is not conducive to CO_2 geological storage and injection construction [40]. The basin-level

suitability evaluation result is moderately suitable. The zone-level suitability evaluation results are as follows: the eastern slope is "moderately suitable", and the central depression is "suitable" (see Figure 6).

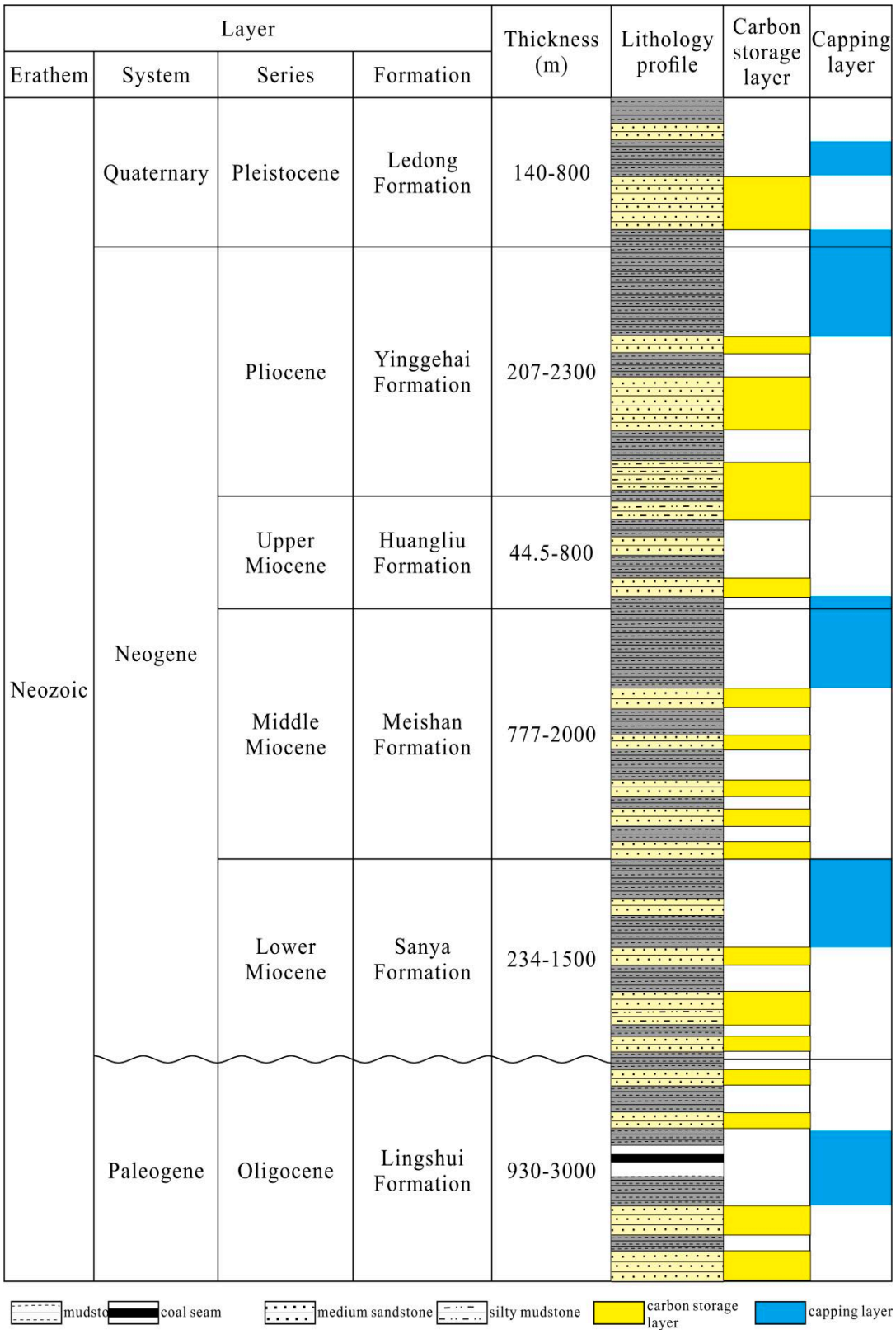

Figure 5. Out–of–scale columnar section of CO_2 storage reservoir and cap rock in the saline aquifers of the Yinggehai Basin.

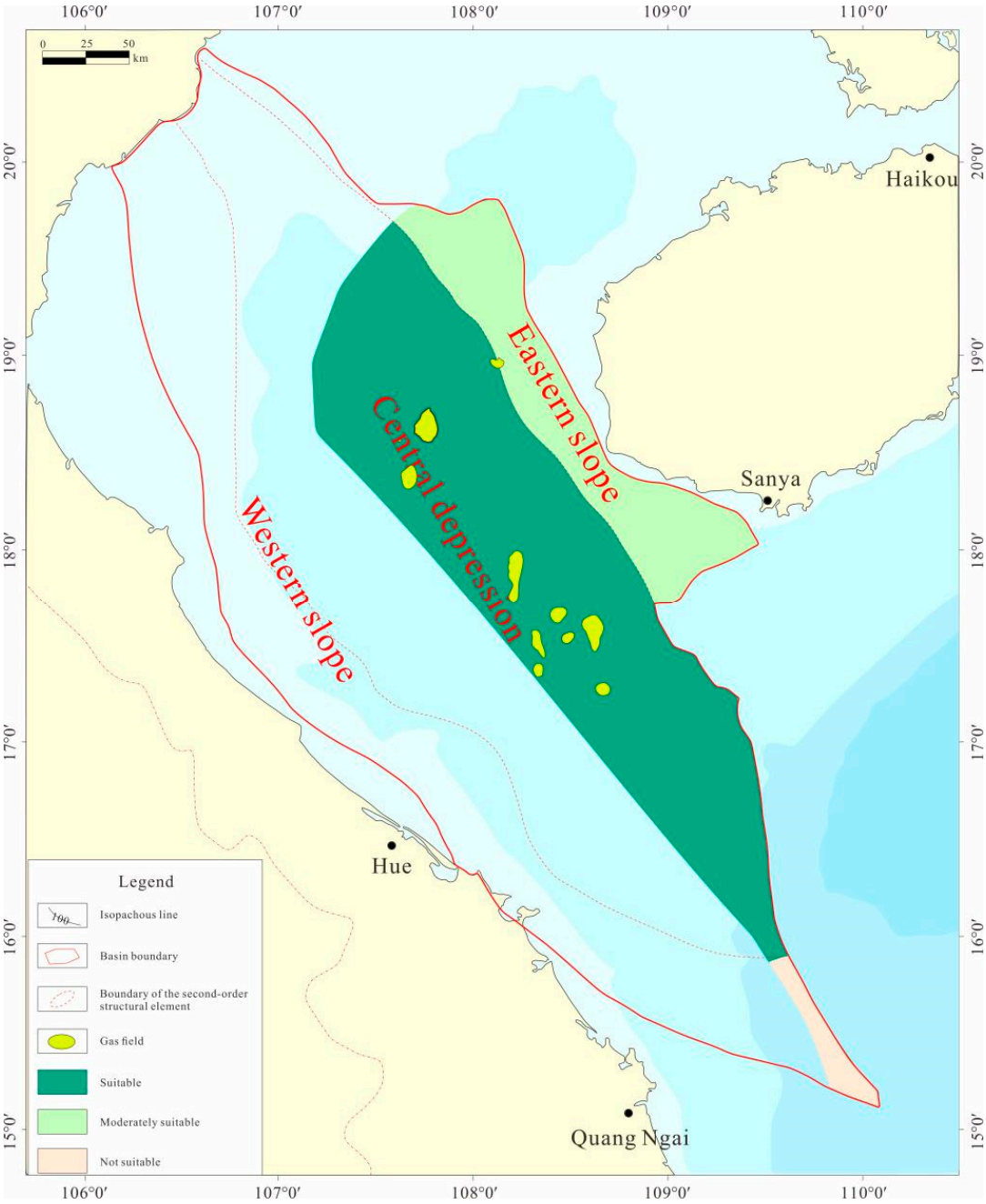

Figure 6. Results of suitability evaluation for belt-level carbon sequestration in the Yinggehai Basin.

5.2. Carbon Sequestration Potential and Suitability Evaluation of the Qiongdongnan Basin

(1) Geological Characteristics for Carbon Sequestration

The Qiongdongnan Basin is situated between Hainan Island and the Xisha Islands in the northern part of the South China Sea. It is adjacent to Hainan Province and Guangdong Province, covering an area of approximately 96,000 square kilometers. The water depth in the northwestern part ranges from 0 to 200 m, with an average of 121 m, while in the southeastern part, it ranges from 200 to 2970 m, with an average of about 1000 m. The thickness of the Cenozoic strata ranges from 500 to 14,000 m (Figure 7). Within the depth range of 800 to 3200 m, two sets of storage–cap rock combinations are developed (Figure 8).

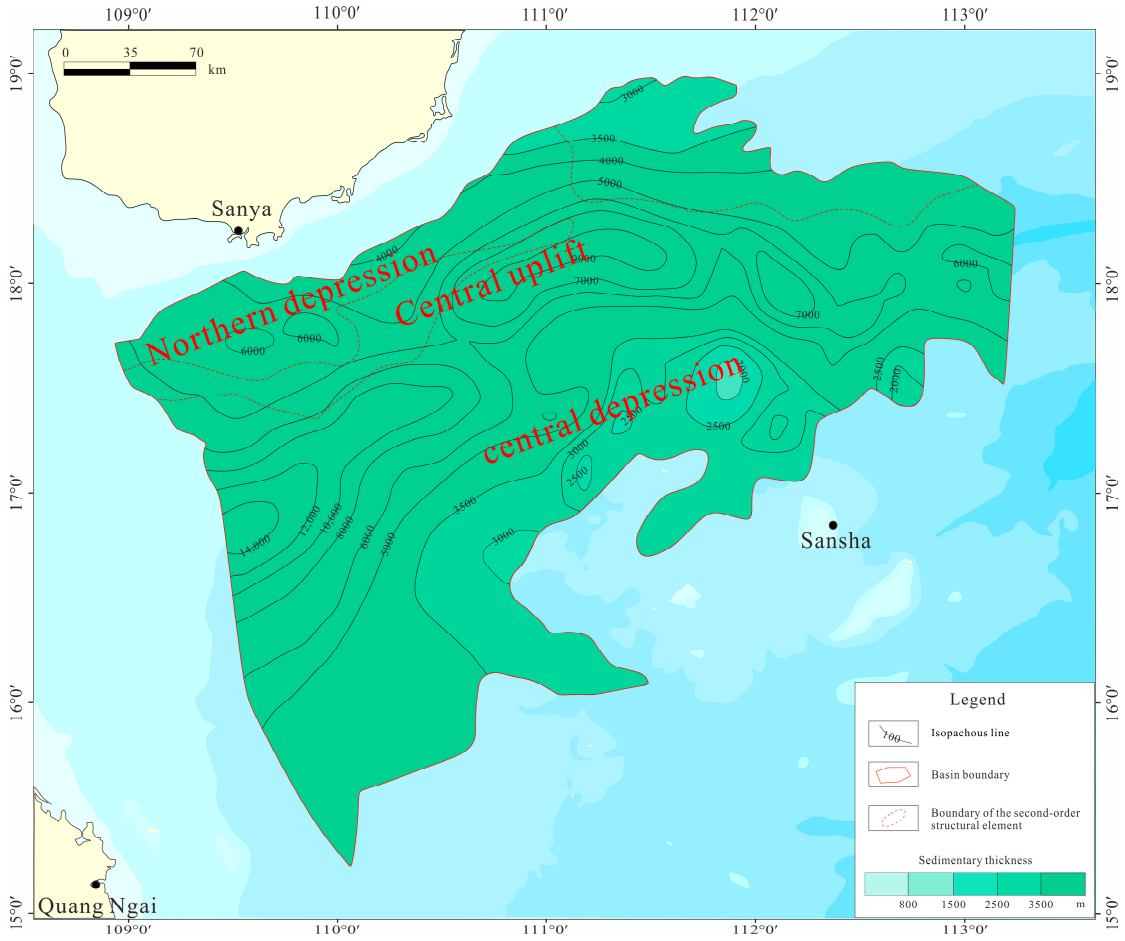

Figure 7. Map of Cenozoic thickness in the Qiongdongnan Basin.

The deltaic and coastal sandstone of the Lingshui Formation, with porosities ranging from 10% to 17%, serve as effective to good storage layers. The underlying mudstone of the Sanya Formation acts as the cap rock. Additionally, the coastal and deltaic sandstone of the Sanya–Meishan Formations, with porosities between 10% and 20%, also function as effective to good storage layers. The overlying mudstone of the Huangliu and Yinggehai Formations acts as the cap rock. The basin has a moderate geothermal gradient, averaging 40 °C/km. The seismic activity within the basin is low, and the crustal stability is high.

The water depth of the Qiongdongnan Basin gradually increases (compare the data in Table 4) from the northwest to the southeast, and the geothermal gradient varies widely, ranging from 25 to 61 °C/km. The average gradient for the basin is 40 °C/km, with the central uplift averaging 39 °C/km, the central depression at 40 °C/km, and the northern depression at 37 °C/km (Table 4).

Table 4. Data table of geothermal gradient, seafloor temperature, and water depth for various zones in the Qiongdongnan Basin.

Basin and Zone	Geothermal Gradient (°C/km)	Seafloor Temperature (°C)	Water Depth (km)
Qiongdongnan Basin	40	5	1
Central Uplift	39	15	0.15
Central Depression	40	5	1
Northern Depression	37	20	0.1

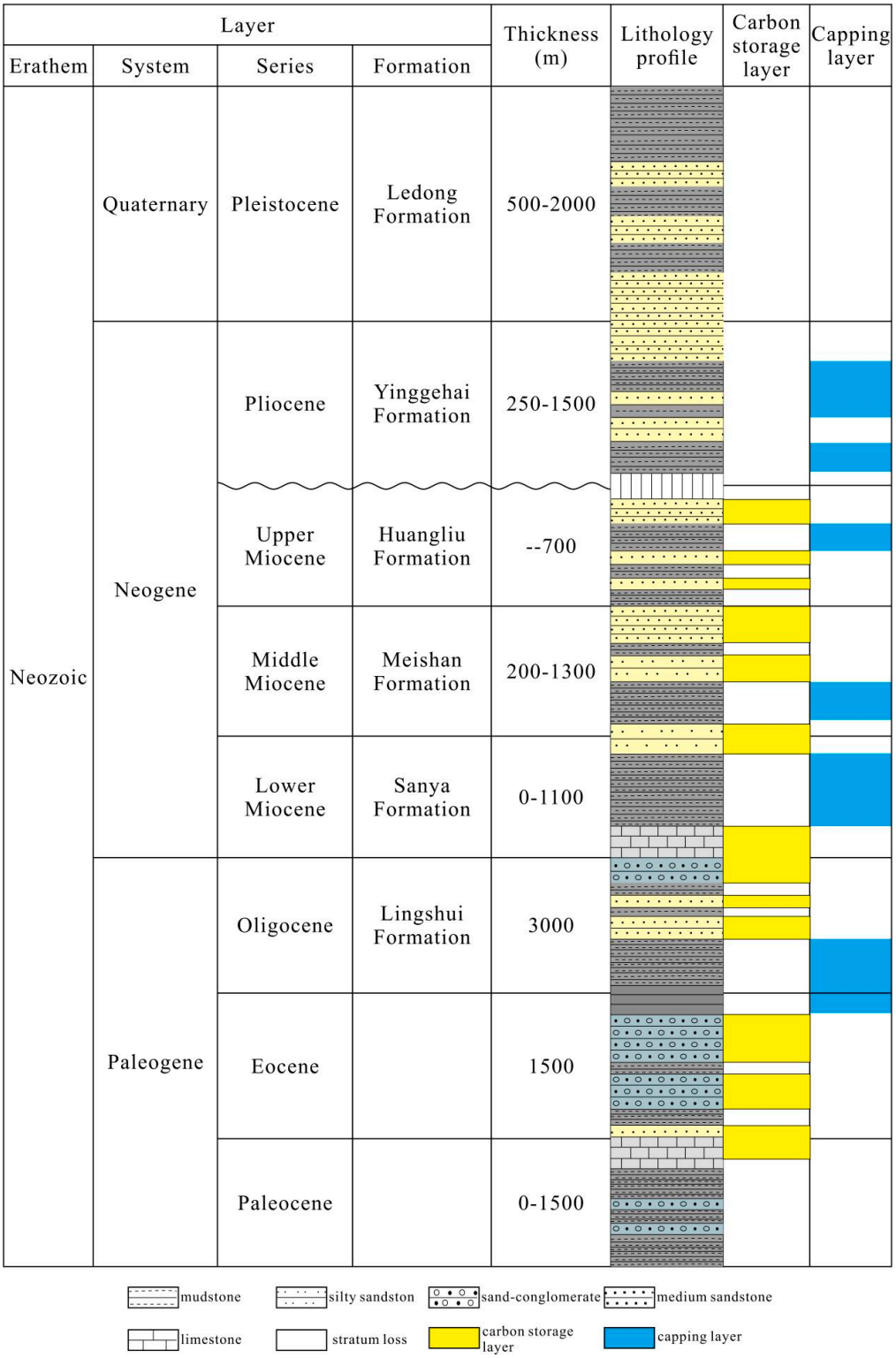

Figure 8. Out–of–scale columnar section of CO_2 storage reservoir and cap rock in the saline aquifers of the Qiongdongnan Basin.

The calculated CO_2 density for the Qiongdongnan Basin at depths between 800 and 3200 m ranges from 678 to 822 kg/m^3. In the central uplift area, the density is between 415 and 573 kg/m^3, while in the central depression, it ranges from 678 to 822 kg/m^3. In the northern depression, the CO_2 density varies from 353 to 568 kg/m^3.

(2) Results of Carbon Sequestration Potential and Suitability Evaluation

The results of the CO_2 geological sequestration potential and suitability evaluation for the Qiongdongnan Basin are shown in Table 5. The estimated potential at the basin level is 2615 billion tons, while the projected potential at the zone level amounts to 2348 billion tons.

Table 5. Results table for carbon sequestration potential evaluation in the saline aquifers of the Yinggehai–Qiongdongnan Basin.

Level	Basin and Zone	Area (within National Boundaries) km^2	Porosity	Sand-to-Shale Ratio	CO_2 Density (kg/m^3)	Effective Sequestration Potential of Basin/Zone ($\times 10^8$ t)			Sequestration Potential per Unit Area ($\times 10^4$ t/km^2)
						E1 = 1.2%	E2 = 2.4%	E3 = 4.1%	
Basin Level	Yinggehai Basin	46,929	0.11–0.29	0.3	263–518	303	606	1036	129
Zone Level	Central Depression	35,273		0.31	289–560	273	546	932	155
	Eastern Slope	10,437		0.29	269–528	66	131	224	126
	Western Slope	1218		0.29	269–528	7	13	22	108
Basin Level	Qiongdongnan Basin	96,289	0.18–0.26	0.32	678–822	1307	2615	4467	272
Zone Level	Central Uplift	13,119		0.34	415–573	133	265	453	202
	Central Depression	71,466		0.3	678–822	972	1943	3320	272
	Northern Depression	11,704		0.34	353–568	70	140	240	120

The basin is generally in the early stages of natural gas reservoir development [41,42]. As of 2021, there are 84 wells in the basin, with significant variations in water depth, short transportation distances, and locally comprehensive engineering data. The basin-level suitability evaluation result is moderately suitable (see Figure 9). The zone-level evaluation results are as follows: the northern depression is "suitable", the central uplift is "moderately suitable", and the central depression is "not suitable".

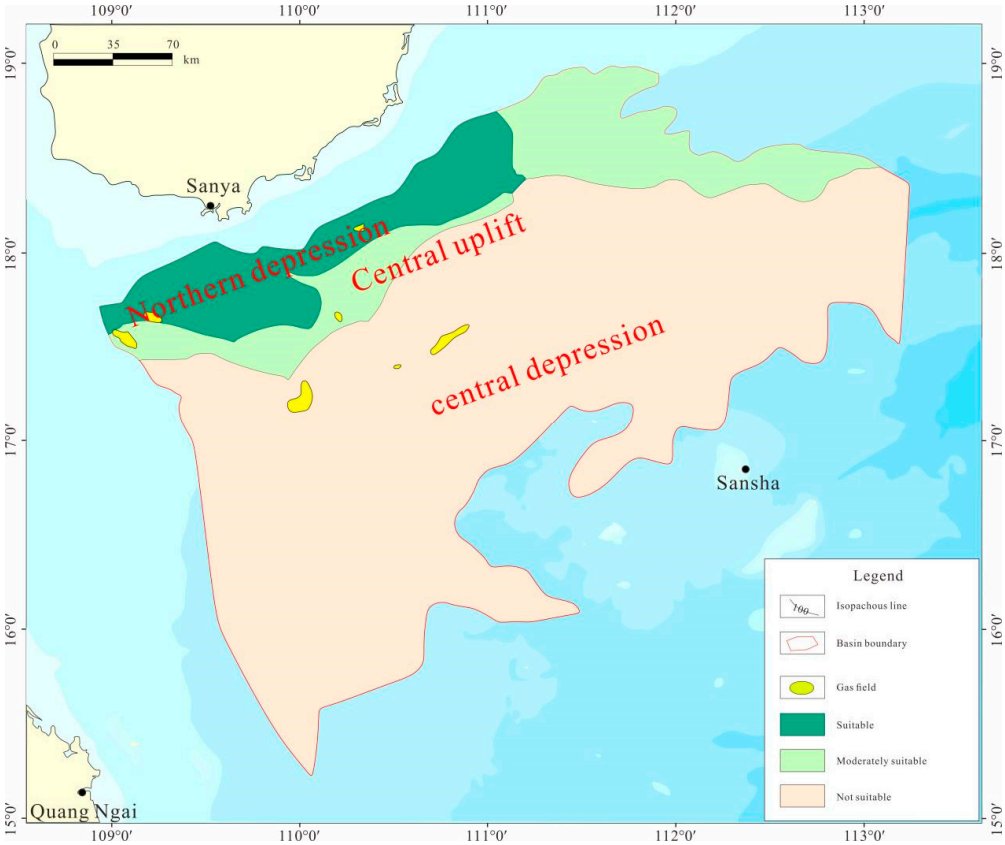

Figure 9. Results map of zone-level carbon sequestration suitability evaluation in the Qiongdongnan Basin.

6. Conclusions

This paper utilizes a hierarchical evaluation method and the volumetric method to comprehensively assess the CO_2 sequestration potential in the saline aquifers of the South Qiongdongnan–Yinggehai Basin. The study results indicate that the basin-level predicted potential for CO_2 geological sequestration in the Yinggehai Basin is 60.6 billion tons, and the zone-level estimated potential is 54.6 billion tons. For the South Qiongdongnan Basin, the basin-level estimated potential is 261.5 billion tons, and the zone-level assumed potential is 234.8 billion tons. These results offer a quantitative assessment of the CO_2 sequestration potential in the region. There may be slight deviations in the assessment of the CO_2 storage potential in the Ledong Formation of the Yinggelai Basin. This deviation is due to the fact that the formation is located at the critical depth for CO_2 storage, with an overestimation range of approximately 10%. This estimate should be considered a factor, but it does not alter our overall positive evaluation of the Yinggelai Basin as a CO_2 storage site.

In terms of suitability evaluation, the Yinggehai Basin is generally considered moderately suitable. The northern depression of the South Qiongdongnan Basin is deemed suitable, the central uplift is moderately suitable, and the central depression is considered unsuitable. These evaluation results take into account geological conditions, engineering conditions, and socio-economic factors, providing crucial decision support for future sequestration projects. Additionally, this study emphasizes the importance of considering these factors holistically to ensure the safety and economic feasibility of sequestration activities.

In summary, the research presented in this document provides a scientific basis for the planning and implementation of CO_2 sequestration projects in the Yinggehai–Qiongdongnan Basin. It offers valuable insights for carbon sequestration efforts in the South China Sea region and beyond. With advancements in technology and supportive policies, these basins hold the potential to become key areas for large-scale CO_2 sequestration, contributing to global climate change mitigation and the achievement of carbon neutrality goals.

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