

## Article

# Structural and Reservoir Characteristics of Potential Carbon Dioxide Storage Sites in the Northern South Yellow Sea Basin, Offshore Eastern China

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**Abstract:** The geological storage of carbon dioxide (CO<sub>2</sub>) in offshore saline aquifers stands as a primary option for reducing CO<sub>2</sub> emissions in coastal regions. China's coastal regions, particularly Shandong and Jiangsu provinces, face significant challenges in CO<sub>2</sub> reduction. Therefore, evaluating the feasibility of CO<sub>2</sub> geological storage in the adjacent seas is critical. To assess the suitability of a CO<sub>2</sub> storage site, understanding its structural and reservoir characteristics is essential to mitigate injection and storage risks. In this study, we analyzed the structural characteristics and potential traps of the Yantai Depression in the South Yellow Sea Basin based on seismic data interpretation. We further conducted well logging analysis and post-stack seismic inversion to obtain lithological data, including acoustic impedance and sandstone content percentages from the Cenozoic Funing Formation, Dainan–Sanduo Formation, and Yancheng Formation. Our findings highlight that the Yantai Depression in the South Yellow Sea Basin exhibits diverse structural traps and favorable reservoir–caprock combinations, suggesting promising geological conditions for CO<sub>2</sub> storage. This area emerges as a suitable candidate for implementing CO<sub>2</sub> geological storage initiatives.

**Keywords:** CO<sub>2</sub> storage; structural traps; reservoir characteristics; seismic inversion; petrophysical analysis



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## 1. Introduction

Reducing carbon dioxide (CO<sub>2</sub>) emissions has become a consensus and concerted action goal among the international community [1–4]. Managing CO<sub>2</sub> greenhouse gas emissions is critical for urban lifeline systems [5]; ensuring the quality of human settlements; and safeguarding the safety of residents' lives [6], property, and ecological security [6,7]. In September 2020, China proposed the dual carbon goal at the 75th United Nations General Assembly, aiming for carbon peak by 2030 and carbon neutrality by 2060 [8]. Developing carbon dioxide capture, utilization, and storage (CCUS) technology vigorously is strategic for China's emission reduction and energy security goals, as well as crucial for building ecological civilization and achieving sustainable development [9,10]. The China CCUS Annual Report (2021), issued by the Institute of Environmental Planning under the Ministry of Ecology and Environment, forecasts that CCUS technology will contribute significantly to emission reductions, aiming for 600 million to 1.4 billion tons by 2050 and an additional 1 to 1.8 billion tons by 2060, aligned with carbon-neutral targets. Widely recognized as the most effective method for lowering CO<sub>2</sub> emissions [10], CCUS involves CO<sub>2</sub> geological storage, where CO<sub>2</sub> captured from industrial sources is injected into geological formations at depths ranging from 800 to 3500 m underground. This process

utilizes structural trapping, residual trapping, solubility trapping, and mineral trapping mechanisms to securely store CO<sub>2</sub> within geological formations [11]. CO<sub>2</sub> geological storage has been proven effective through global pilot, applicable to suitable geological formations such as onshore and offshore saline aquifers [12–15], as well as depleted oil and gas fields [16–18]. Submarine saline aquifers, in particular, offer advantages in terms of greater storage potential, enhanced safety, and reduced environmental risks compared to terrestrial options, making them a preferred choice for coastal regions pursuing CO<sub>2</sub> geological storage solutions.

The South Yellow Sea Basin, situated in the southern part of the Yellow Sea adjacent to Shandong and Jiangsu provinces in China, recorded CO<sub>2</sub> emissions of 937 and 804 Mt, respectively, in 2019, with Qingdao City (Shandong Province) alone emitting 49 Mt of CO<sub>2</sub> [19,20]. Consequently, there is a pressing need for offshore geological CO<sub>2</sub> storage in these provinces. Evaluation of CO<sub>2</sub> storage potential in offshore China estimates that Cenozoic strata in the South Yellow Sea Basin can store between 39.59 Gt and 426.94 Gt (average: 155.25 Gt), sufficient to meet demands of Shandong and Jiangsu provinces for approximately 89 years. Specifically, the Yantai Depression in the northern South Yellow Sea Basin, characterized by lower geothermal gradients, ground heat flow values, seismic activity, and higher storage potential (approximately twice that of the Qingdao Depression in the southern South Yellow Sea Basin), emerges as the optimal area for CO<sub>2</sub> storage [21].

Structural traps are pivotal in CO<sub>2</sub> geological storage, influencing long-term CO<sub>2</sub> storage viability. Understanding these trap characteristics is crucial for site assessment [22]. Furthermore, assessing the integrity and sealing capacity of reservoir caps enclosing storage zones is essential for ensuring the stability and security of stored CO<sub>2</sub> over time. This study focuses on utilizing drilling data, seismic interpretation techniques, and post-stack seismic inversion analysis to comprehensively assess structural trap characteristics and sandstone reservoir properties within the Cenozoic formations of a promising CO<sub>2</sub> storage site located in the Yantai Depression. Seismic data provide critical insights into subsurface geology, enabling the mapping of structural features and identification of potential trap configurations. By integrating these techniques, we aim to thoroughly evaluate CO<sub>2</sub> storage potential in the Yantai Depression, laying the foundation for selecting an ideal site for a CO<sub>2</sub> storage demonstration project. This assessment is crucial for pinpointing optimal locations, advancing sustainable CO<sub>2</sub> storage solutions, and mitigating climate change impacts.

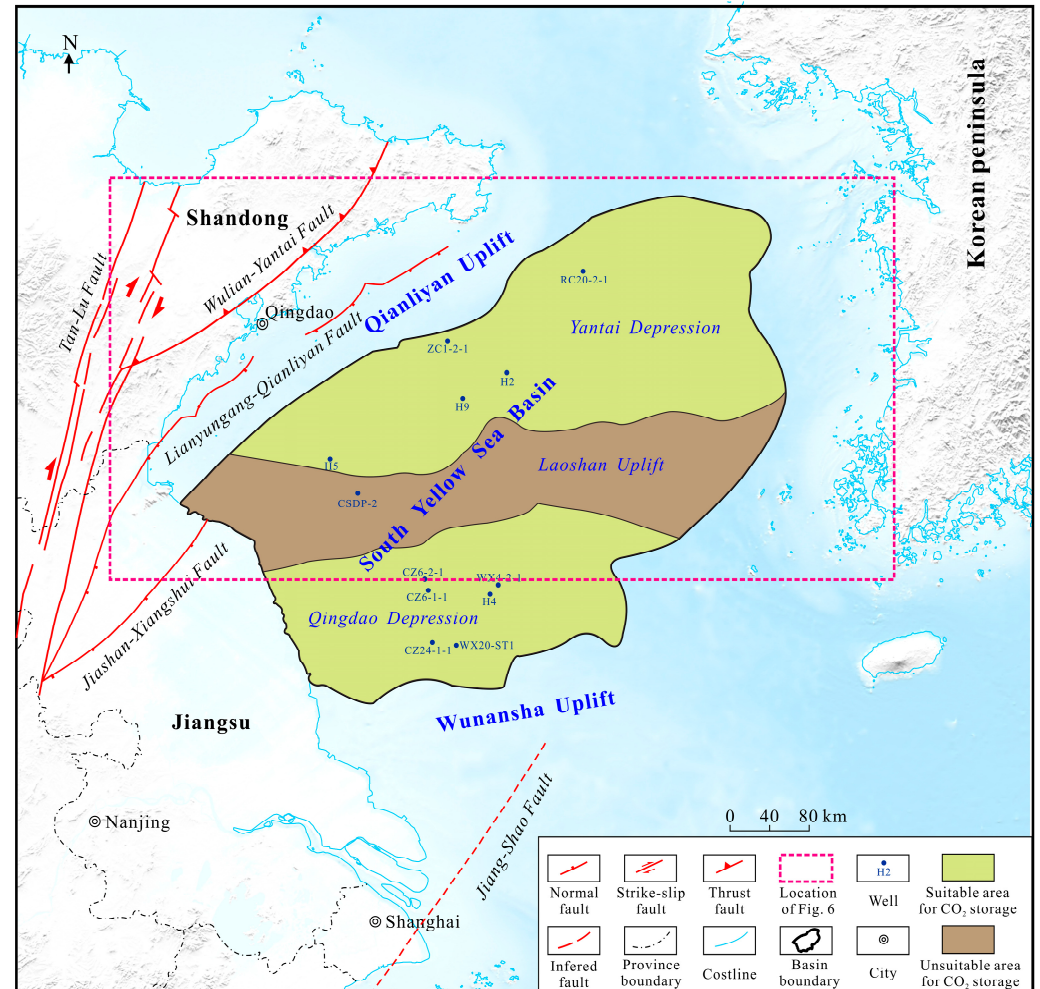
## 2. Geologic Setting and CO<sub>2</sub> Storage Potential

### 2.1. Geologic Background

The South Yellow Sea encompasses the southern offshore area between mainland China and the Korean Peninsula, spanning approximately  $3.2 \times 10^5$  km<sup>2</sup> [23,24]. Situated within the northeast Yangtze Block of the South China Plate, it is flanked by the Wunansha Uplift to the south and the Qianliyan Uplift to the north (Figure 1). This extensive sedimentary basin overlays both Mesozoic–Paleozoic oceanic and Mesozoic–Cenozoic terrestrial sedimentary basins [21,25], encompassing strata from the Archean–Mesoproterozoic, Neoproterozoic, Paleozoic (Triassic), and Cenozoic (Paleogene and Neogene) periods [23].

Regional tectonic movements have been frequent since the Neoproterozoic, including the Jinning, Indosinian, Yanshanian, and Himalayan movements, characterized by both extrusion and extension [25]. The Jinning movement (800 Ma) led to the formation of the ancient Yangtze Block. After the Jinning movement, the region reached the platform stage, and thick marine Paleozoic–Triassic strata were formed. The Indosinian movement (205 Ma) caused the extinction of the ancient ocean and the collision between the Yangtze block and the Sino-Korean Blocks, resulting in uplift and the emergence of terrestrial conditions. The Yanshanian movement (66 Ma) triggered significant magmatic activity and marked the beginning of an extensive stress stage, leading to the formation of terrestrial Paleogene fault basins. The Himalayan movement (23 Ma) caused brief uplift, followed by a prolonged subsidence phase during the Neogene, leading to stable sedimentation with fewer fractures and folds. The present tectonic pattern, characterized by “one uplift

between two depressions” in the South Yellow Sea Basin, is controlled by the major Tanlu Fault and subsidiary faults, primarily trending NE–SW, followed by E–W and NW–SE orientations [26]. This tectonic framework divides the basin into the Yantai Depression, Laoshan Uplift, and Qingdao Depression from north to south (Figure 1).



**Figure 1.** The regional location of the South Yellow Sea Basin (modified from Yuan et al., 2023 [21]).

Oil and gas exploration in the South Yellow Sea Basin began in the early 1960s, and by 2021, a total of 30 wells had been drilled, revealing Upper Silurian and younger strata [26,27]. Among them, wells H2, H5, H7, H9, ZC1-2-1, and RC20-2-1 in the Yantai Depression, as well as CZ24-1-1, WX-20-ST1, WX4-2-1, CZ6-2-1, CZ6-1-1, and H4 in the Qingdao Depression, have fully penetrated Neocene strata [23]. Additionally, well CSDP-2 has completely revealed the Upper Silurian and younger strata in the Laoshan Uplift. The petrophysical properties of Mesozoic reservoirs in the South Yellow Sea Basin are poor, with Paleozoic strata exhibiting extremely tight reservoirs. Sandstone porosity is within 3%, and carbonate porosity is within 4%. Conversely, the average porosity of Cenozoic reservoirs exceeds 10%, making the Cenozoic strata the primary targets for carbon storage. These Cenozoic strata include the Palaeocene Funing Formation, the Eocene Dainan Formation, the Sanduo Formation, and the Neogene Yancheng Formation [28].

The geothermal gradient in the South Yellow Sea basin ranges from 2.4 °C to 3.0 °C/100 m, with an average of 2.93 °C/100 m. The heat flow value ranges from 61 to 66 mW/m<sup>2</sup>, averaging 63.5 mW/m<sup>2</sup>. According to the basin geothermal zoning standard [29], the South Yellow Sea Basin is classified as a “warm basin” suitable for CO<sub>2</sub> geological storage. The geothermal gradient increases gradually from north to south, with the Yantai Depression

exhibiting the lowest values. Although there is no obvious north–south zonation, the mean heat flow in the Yantai Depression is also lower than that in the Qingdao Depression. Historical records indicate that from 1495 to 2015, a total of 18 earthquakes of magnitude 6 or above occurred in the South Yellow Sea Basin. Of these, 16 were recorded in the southwest of the basin (west of the Qingdao Depression and Laoshan Uplift), and only 2 in the north of the basin [30]. In the past 100 years, there have been only two earthquakes of magnitude 6–7, both in the Qingdao Depression. Therefore, from a seismic activity perspective, the stability of the Yantai Depression is better than that of the Qingdao Depression and Laoshan Uplift [21].

## 2.2. CO<sub>2</sub> Storage Potential

Various methods have been employed to estimate the CO<sub>2</sub> storage potential of the saline aquifer in the South Yellow Sea Basin. Li et al. [31] estimated the CO<sub>2</sub> storage capacity to be 133.8 Gt using the dissolution method. Huo [32] used the USDOE calculation method to estimate a CO<sub>2</sub> storage capacity of 113.4 Gt for the saline aquifer at a depth of 800–3500 m. Yuan et al. [21] calculated the CO<sub>2</sub> storage capacity using an improved USDOE method, finding an average storage capacity of 155.25 Gt at depths of 800–3200 m ( $E = 2\%$ ), with a range from 39.59 Gt ( $E = 0.51\%$ ) and 426.94 Gt ( $E = 5.5\%$ ). The estimated CO<sub>2</sub> storage capacity of the Yantai Depression saline aquifer (800–3200 m) ranges from 25.25 to 272.25 Gt, with an average of 99 Gt. For the Qingdao Depression saline aquifer (800–3200 m), the capacity ranges from 11.94 to 128.79 Gt, with an average of 46.83 Gt. Using the improved volumetric method, the average CO<sub>2</sub> storage potential of the brackish layer at 800–3200 m depth in the South Yellow Sea Basin is also calculated to be 155.25 Gt ( $E = 2\%$ ), with a minimum of 39.59 Gt ( $E = 0.51\%$ ) and a maximum of 426.94 Gt ( $E = 5.5\%$ ). In terms of storage suitability, the Cenozoic layer thickness in the Laoshan Uplift is less than 800 m, rendering it unsuitable for CO<sub>2</sub> storage. The average CO<sub>2</sub> storage potential in the Yantai Depression is about twice that of the Qingdao Depression. Additionally, the seismic activity and geothermal conditions in the Yantai Depression are more favorable for CO<sub>2</sub> storage than those in the Qingdao Depression. Therefore, the Yantai Depression is considered more suitable for CO<sub>2</sub> storage in the saline aquifer [21].

## 3. Dataset and Methodology

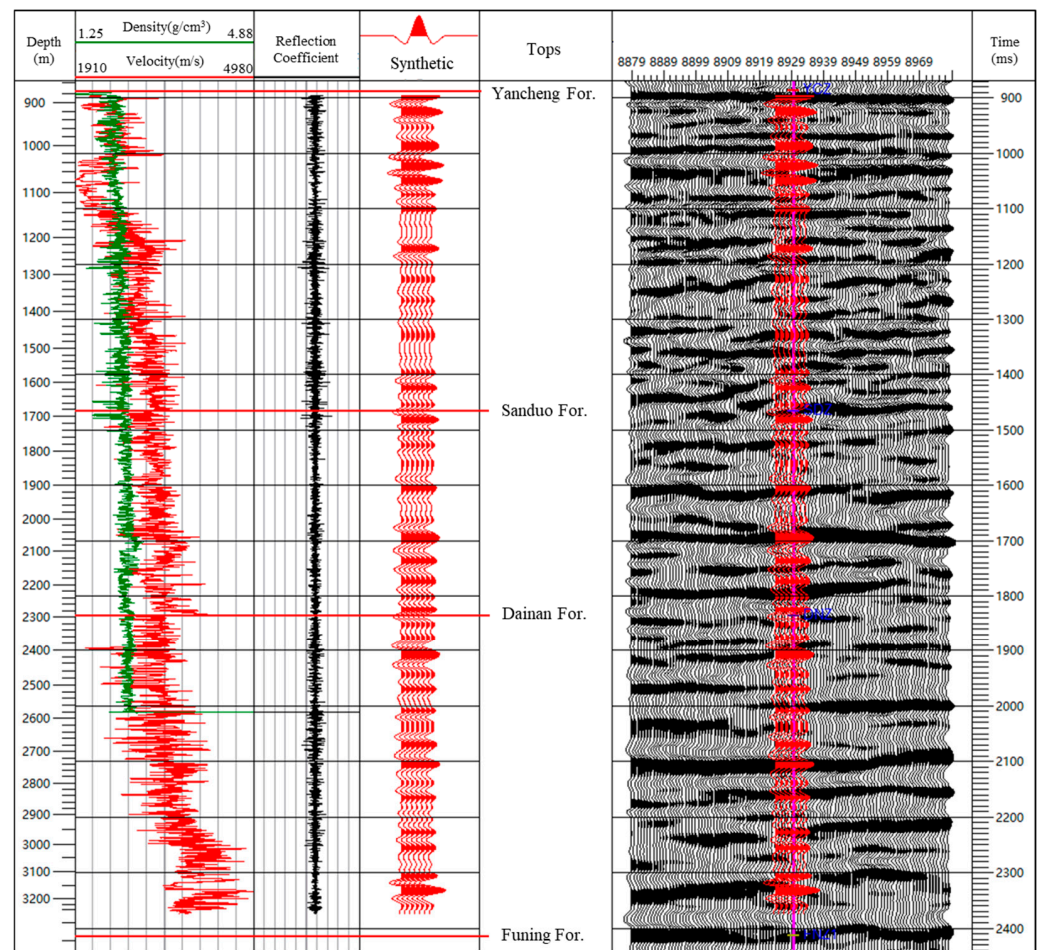
### 3.1. Dataset

The dataset of this study included 27,628 km of 2D seismic data from the Yantai Depression. We have collected post-stack seismic data, as pre-stack seismic data were not available. West of 123° E, the survey grid density was  $4 \times 8$  km, whereas east of 123° E, the density was  $10 \times 20$  km. Additionally, we have collected logging data from six drilling wells, including H2, H5, H7, H9, ZC7-2-1, and ZC1-2-1. The logging data comprised sonic wave travel time (DT), gamma-ray (GR), spontaneous potential (SP), and resistivity measurements. Density log data were available for only two of the wells.

### 3.2. Seismic Interpretation

The 2D seismic data were interpreted using the Petrel Software Platform (version 2016), with well control as a constraint. By utilizing 1D synthetic seismograms, we effectively correlated different seismic reflectors with their corresponding stratigraphic markers, achieving a tight integration of seismic and well data. The ZC1-2-1 well data were utilized to link each geologic interface with its corresponding seismic reflection. Synthetic seismograms, produced by convolving the reflectivity series (calculated from density and sonic logs) with extracted wavelets, were employed, with statistical wavelets extracted from the seismic data being adopted. Figure 2 shows the well-to-seismic tie results for well ZC1-2-1, where the red traces represent the synthetic data, and the actual seismic data are represented by the waveform, demonstrating a high correlation between them. Fault interpretation was conducted manually, while horizon interpretation utilized 2D seeded auto-tracking where possible.





**Figure 2.** A synthetic seismogram of well ZC1-2-1.

### 3.3. Wireline Logging Data Analysis and the Petrophysical Model

The complete logs from the 6 wells included gamma-ray curves, although sonic logs were not recorded at shallower depths in some wells. To compensate for these missing sections, linear regressions from the shallowest zones containing both the sonic and gamma-ray data were used to generate synthetic sonic logs (Figure 3). The density log data were calculated using Gardner's equation [33]. The volume of shale ( $V_{shale}$ ) was calculated using the Clavier method [34] based on the gamma-ray logging data (Figure 4).

### 3.4. Post-Stack Seismic Inversion

Acoustic impedance (AI), a product of rock density and seismic velocity, can be used as an important indicator of lithology and petrophysical properties, both critical factors in  $CO_2$  storage assessment. Extracting AI properties from seismic data requires seismic inversion, which converts seismic reflection amplitudes into impedance profiles. In this study, we adopted the colored inversion approach proposed by Lancaster et al. (2020) [35]. The method involved fitting the average well-log AI spectra to the average seismic spectra to produce an operator that matches the amplitude spectrum of the seismic data with the corresponding AI data from the well logs. Subsequently, this operator was convolved with the seismic traces to estimate AI. The colored inversion methodology was computationally efficient and robust, eliminating the need for wavelet extraction, reducing the influence of human factors in inversion, and allowing for an objective representation of geological phenomena. The principle of colored inversion involves obtaining a matching operator by fitting the spectra of seismic and well logging data. Figure 5 illustrates the extraction process of the inversion operator: the left column of the first section shows curves after

energy fitting of a single-well AI, while the right column displays smoothed curves of seismic trace AI energy. The left image of the second section depicts the energy-matching curves between single-well and seismic trace, with the red curve representing the matching operator. The right image shows the time-domain morphology of the transformed factor after matching. Applying this matching operator to invert the seismic data produces an AI inversion profile.

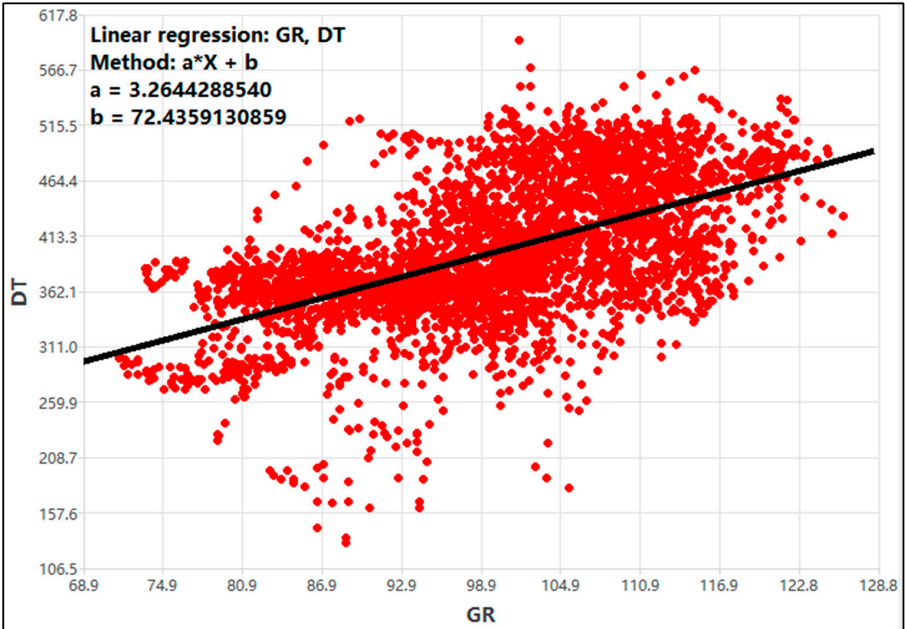


Figure 3. Cross-plots of gamma-ray (GR) versus DT.

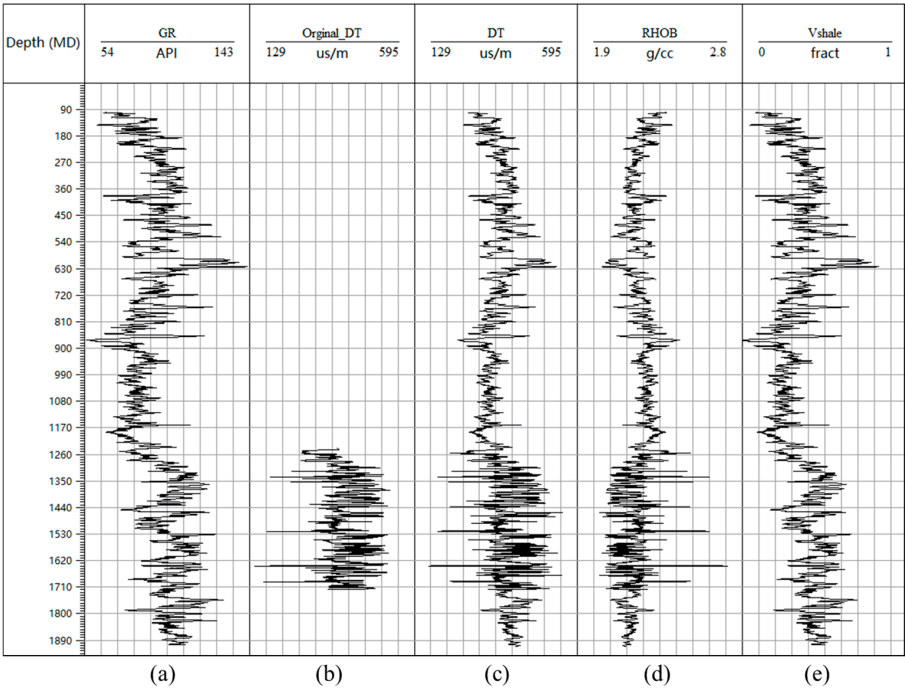
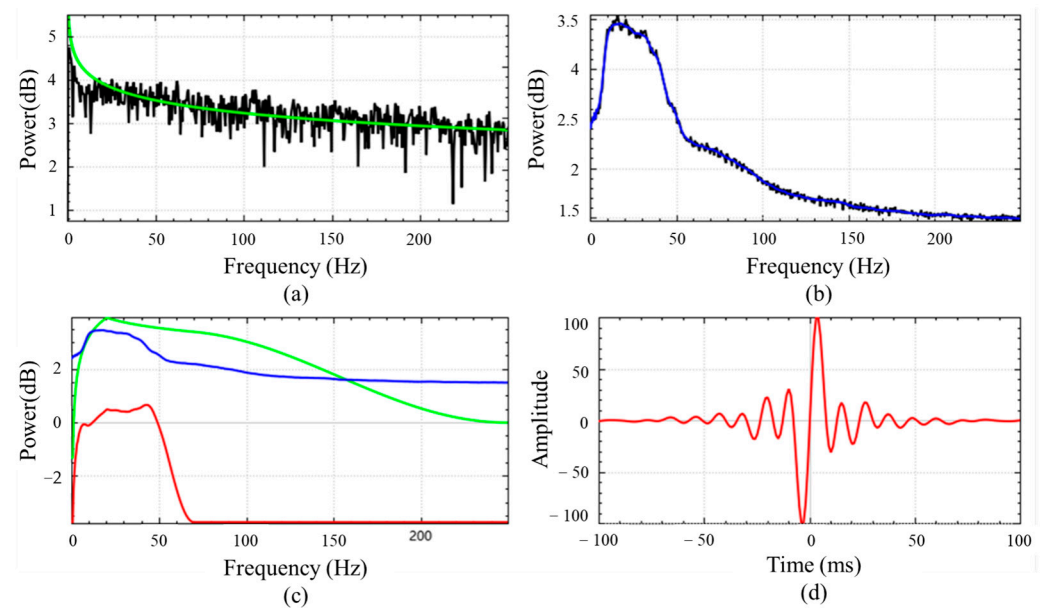


Figure 4. Logging data of well H9 in the Yantai Depression, South Yellow Sea Basin. (a) Gamma-ray (GR) logging data; (b) original DT logging data; (c) DT compensate for missing sections in the shallowest zones by GR; (d) RHOB calculated using Gardner’s equation; (e) the volume of shale (Vshale) calculated using the Clavier method based on GR logging data.



**Figure 5.** The extraction process of the colored inversion operator. (a) The curves after energy fitting of single-well AI. (b) The smoothed curves of seismic trace AI energy. (c) The energy matching curves between single-well and seismic trace, with the red curve representing the matching operator. (d) The time-domain morphology of the transformed factor after matching.

## 4. Results

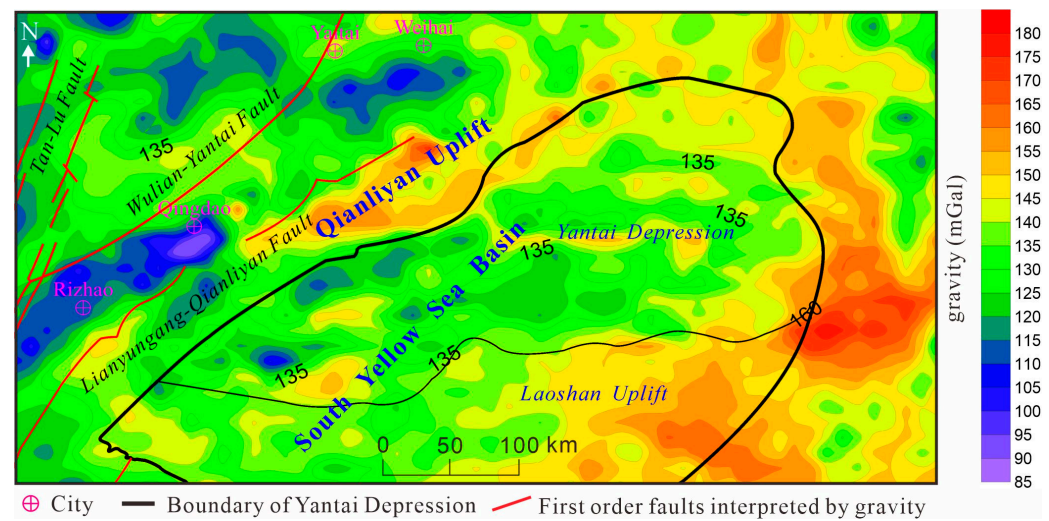
### 4.1. Structural Characteristics of the Yantai Depression

#### 4.1.1. Regional Tectonic Characteristics and Cenozoic Tectonic Movement

The Yantai Depression, located in the northern part of the South Yellow Sea Basin, is an extensional fault basin formed under the right-lateral strike-slip influence of the Tanlu and Qianliyan faults during the Cretaceous and Paleogene periods. The northern boundary of this depression, the Qianliyan Fault, is a south-dipping, NEE-trending tensile-torsional normal fault, controlled by a series of nearly east–west trending normal faults. This has resulted in a tectonic framework composed of grabens, half-grabens, and bulges, exhibiting alternating sag and swell structures with characteristics of north–south zoning and east–west segmentation. The Bouguer gravity anomaly (Figure 6) manifests as a parallel arrangement of beaded positive and negative anomalies, reflecting the undulating basement of the pre-Mesozoic era and the alternating concave–convex tectonic framework. The Paleogene inherited the structural characteristics of the Mesozoic and pre-Mesozoic eras.

The tectonic movement in the Yantai Depression exhibits a cyclicity from simplicity to complexity and back to simplicity. In the early stage, during the Taizhou Formation period, apart from the normal faults that control the boundary of fault depression, faults and folds were not well developed, representing a period of simple half-graben depression. During the Funing Formation period, with the expansion of the fault depression, the depression range enlarged, leading to a series of tensile normal faults and fault-related structures, resulting in a gradual increase in structural development. From the Dainan and Sanduo Formations to the early Neogene, the tectonic movement entered a stage of intense complexity, characterized by the following: (1) The simultaneous occurrence of tensile and compressive fault activities, forming a structural pattern with intertwining normal and reverse faults. (2) The development of positive inversion structures. During the early Cenozoic era, tensile forces mainly led to the formation of normal faults. However, due to the intense compression of the Sanduo movement, the descending plate of the fault reversed into the ascending plate, causing the normal faults to develop into reverse faults, thus forming inversion structures. (3) Intense erosion from the Upper Yancheng Formation of the Neogene to the upper part of the Funing Formation of the Paleogene, such as the Zhucheng 7-2-1 structure. From the Lower Yancheng Formation of the Neogene

to the Quaternary period, the tectonic regime returned to a simple phase, with subsidence dominating and fault structures becoming less developed.



**Figure 6.** Bouguer gravity anomaly in the Yantai Depression, South Yellow Sea Basin (WGS2012 gravity model).

#### 4.1.2. Structural Trap Types

The relatively complex tectonic movements in the Yantai Depression have led to diverse structural styles and local structures, resulting in various types of structural traps. The primary structural traps in the study area are as follows:

- Thrust anticline

The normal faults formed by early extension were structurally reversed under the strong compressional stress of the Sanduo movement at the end of the Paleogene. This led to large-scale folding, uplifting, and arching of the Paleogene and basement rocks, resulting in the formation of thrust anticline structures. Subsequent erosion caused extensive missing of the Sanduo and Dainan Formations, as well as partial missing sections in the Funing Formation. For instance, Figure 7a,b show structures where the Sanduo–Dainan Formation is missing at the peak of the structure.

- Collapsed anticline

The lateral compressional anticlines formed by slope collapse and gravity compression during extensional movements typically manifest as an anticline or half-anticline structure, with folds and uplifts in the Paleogene layers while the basement maintains a slope and depression morphology (Figure 7c). This type of structure is a relatively significant trap in the Yantai Depression.

- Compressional anticline

The anticlinal structure formed due to the lateral compression of the regional stress field, causing folding and deformation (Figure 7d).

- Faulted anticline

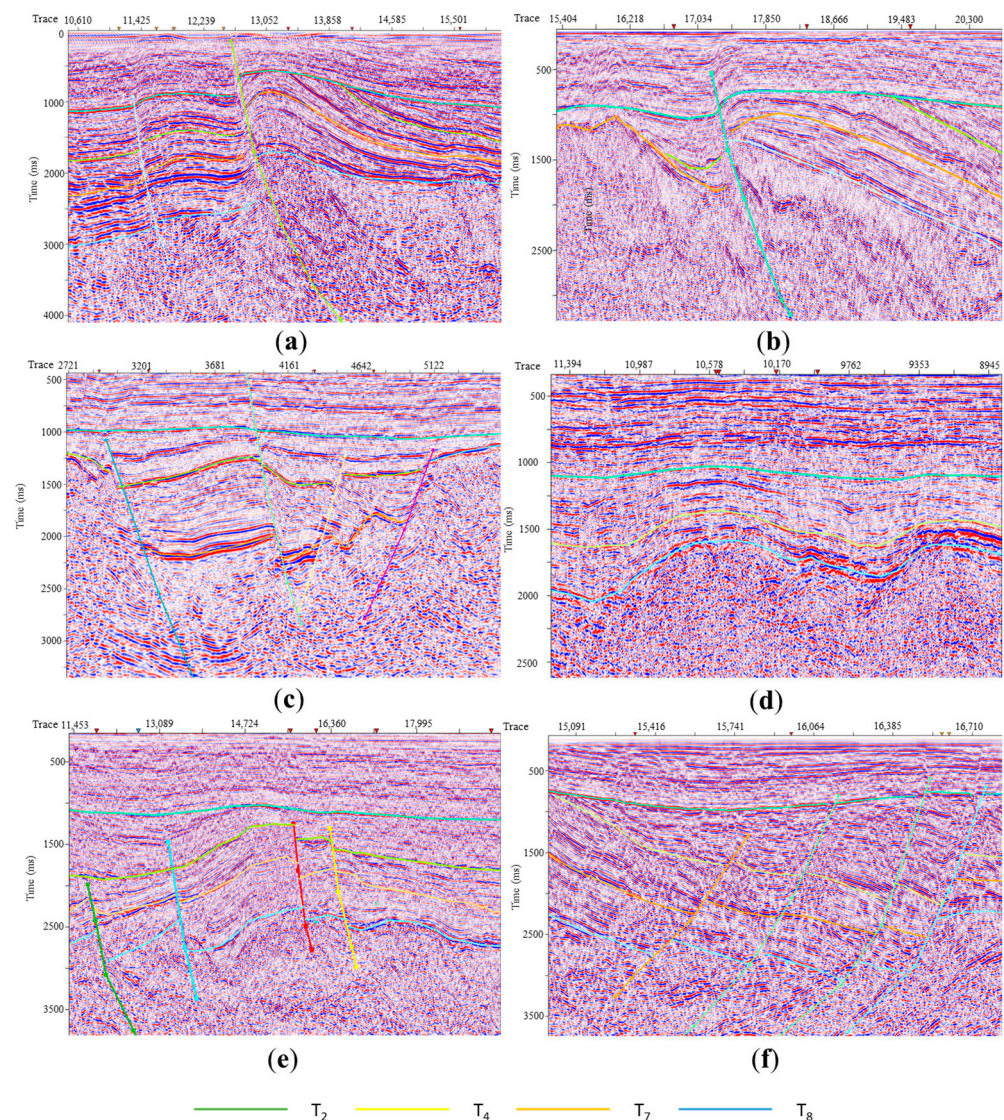
An anticline truncated by a fault, resulting in a structure comprised of half an anticline and the fault, is shown in Figure 7e. These anticlines are typically controlled by second- or third-order faults and are relatively widespread in the Yantai Depression. This type of structure is similar to the trap type in the German Ketzin project.

- Fault block structure

These structures form at the intersection of three directions cut by two or more faults, as shown in Figure 7f. They are generally distributed along the edges of depressions,



formed early, and have undergone long-term development, serving as one of the primary trap types in the study area.

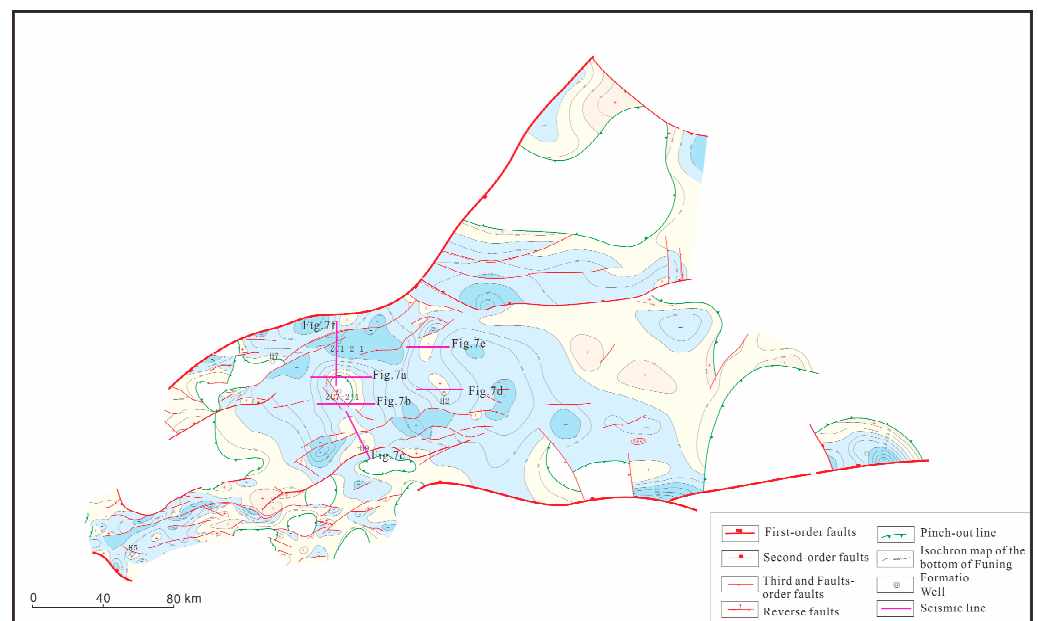


**Figure 7.** Various types of structural trap in the Yantai Depression, South Yellow Sea Basin. (a,b) Trust anticline. (c) Collapsed anticline. (d) Compressional anticline. (e) Faulted anticline. (f) Fault block structure. T<sub>2</sub>: bottom of the Yancheng Formation; T<sub>4</sub>: bottom of the Sanduo–Dainan Formation; T<sub>7</sub>: bottom of the Funing Formation; T<sub>8</sub>: bottom of the Taizhou Formation (the location of seismic lines are shown in Figure 8).

#### 4.2. Reservoir Characteristics

##### 4.2.1. Stratigraphic Sequence and Sedimentary Characteristics of the Cenozoic

Based on data from six drilling wells and seismic surveys in the Yantai Depression, the Cenozoic strata range in thickness from 400 to 4000 m. The main formations developed in this area include the Paleogene Funing Formation, Dainan Formation, Sanduo Formation, the Neogene Yancheng Formation, and the Quaternary Dongtai Group. These formations represent diverse geological epochs and sedimentary environments that have shaped the Yantai Depression during the Cenozoic Era.



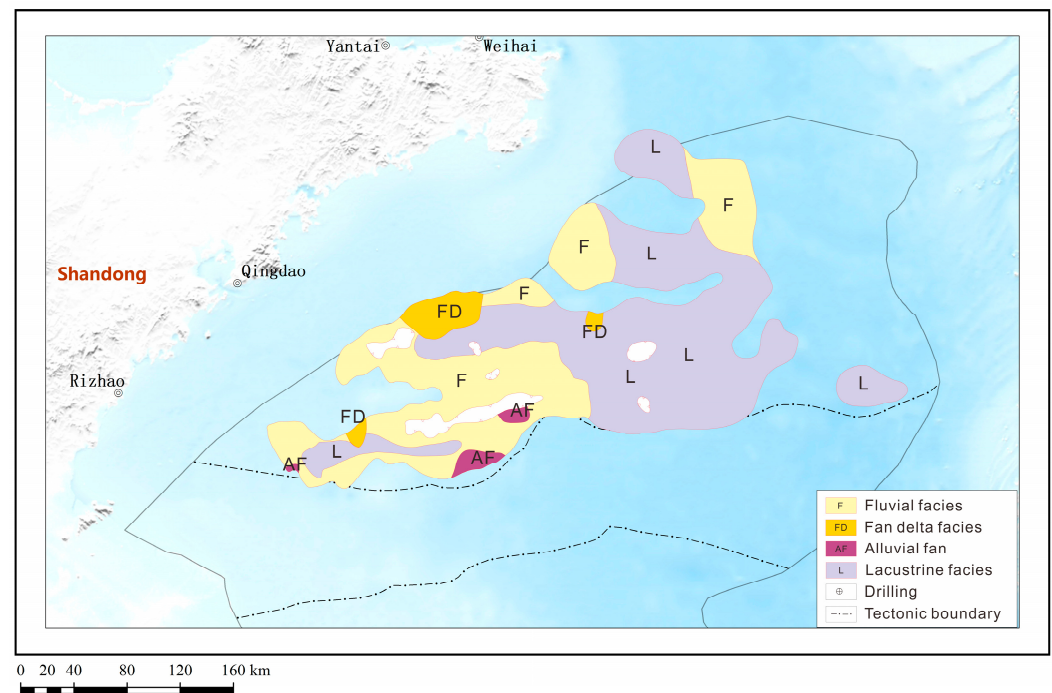
**Figure 8.** Structural map of the Funing Formation in the Yantai Depression.

During the Paleocene Epoch, fault depression development characterized the South Yellow Sea Basin, marked by frequent tectonic activities and widespread deposition of the Funing Formation across the entire region. Initially, deposition consisted of coarse clastic infills from fluvial sources. Subsequent rapid subsidence transformed the basin into a shallow to semi-deep lake environment. As water depth increased, the lake gradually expanded, even flooding the Laoshan Uplift and most of the Wunansha Uplift, forming an extensive lake basin (Figure 9). Deposition during this period also included fluvial, fan delta, alluvial fan, and submarine fan deposits. In the northwestern part of the depression, sedimentary facies transitioned from alluvial fan to fan delta, river, and semi-deep lake facies from the margin to the center. The southwestern part exhibited a sedimentary facies sequence from alluvial fan, river, to shore–shallow lake facies. In the eastern part, sedimentary facies ranged from shore–shallow lake to semi-deep lake facies. Sediments predominantly originated from the Qianliyan Uplift in the northern part of the South Yellow Sea Basin.

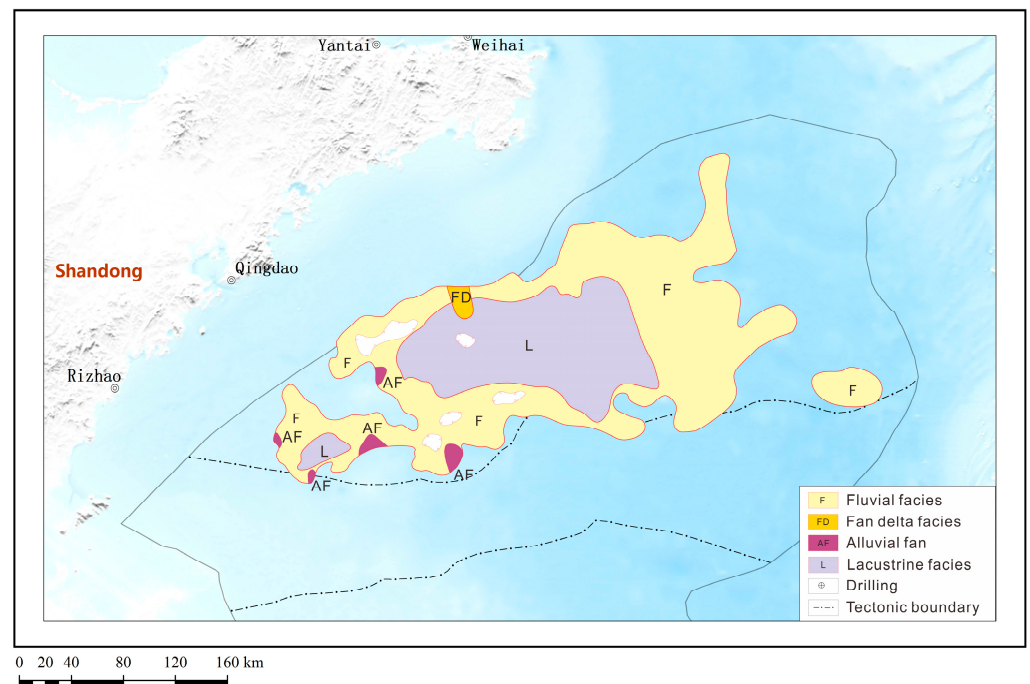
As the Funing Formation deposition concluded, uplift of the basement led to contraction of the lake basin. During the Dainan Formation deposition, fault block movements dominated the South Yellow Sea Basin, uplifting the central area while causing subsidence in the southern and northern basins, resulting in a symmetric half-graben structure flanking the Laoshan Uplift. The Dainan Formation is primarily composed of fluvial facies, with lacustrine facies in the depression centers, albeit with a reduced depositional extent compared to the Funing Formation. Subsequent deposition of the Sanduo Formation flattened the topography of the South Yellow Sea Basin. Concurrent fault activities increased depression subsidence beyond Eocene levels. Early stages witnessed frequent oscillatory movements, distinct sedimentary cycles, and relatively coarse sediments, transitioning to dominance by purple-red mudstones in the late stage. Overall, during the Sanduo–Dainan Formation deposition, fluvial facies predominated, forming a sedimentary association of alluvial fan–fluvial–fan delta–lacustrine facies (Figure 10).

In the early Lower Yancheng Formation, the southern Yantai Depression remained uplifted, receiving thick fluvial deposits only in the northern part. Shallow lacustrine deposits dominated the later stages. The Upper Yancheng Formation is primarily composed of shallow lacustrine and fluvial deposits. The early Quaternary Dongtai Formation featured shallow fluvial deposits, transitioning to fluvio-marine deposits in later stages.





**Figure 9.** Sedimentary facies of the Funing Formation in the Yantai Depression, South Yellow Sea Basin.



**Figure 10.** Sedimentary facies of the Sanduo–Dainan Formation in the Yantai Depression, South Yellow Sea Basin.

#### 4.2.2. Petrophysical Characteristics of the Potential Sandstone Reservoirs

The evaluation of CO<sub>2</sub> storage potential evaluation indicates that the optimal depth range for CO<sub>2</sub> storage in the South Yellow Sea Basin is between 800 and 3200 m below the seabed [21]. According to drilling exploration data, four reservoir sets were identified within the depth range in the Yantai Depression, namely, the upper part of the Funing

Formation, the Dainan Formation, the Sanduo Formation, and the Upper and Lower Yancheng Formation.

A rock physics analysis was conducted to investigate the petrophysical characteristics of these potential sandstone reservoirs. This study primarily utilized data from seven drilling wells across the Yantai Depression, covering logging depths from the Yancheng Formation to the Funing Formation, including the Sanduo and the Dainan formations. All wells provided gamma-ray and sonic logging data, with density logging data available for two wells. Gamma-ray logging data were complete for each well, while missing acoustic logging data for the Yancheng Formation were supplemented using gamma-ray logging data. Bulk density, calculated using Gardener’s formula due to missing density logging in some wells, facilitated the calculation of acoustic impedance. Furthermore, shale content was determined using the method outlined in Section 3. Gamma-ray data were normalized to ensure consistency across all wells (Figure 11). Figure 12 illustrates that gamma-ray readings of sandstone, glutenite, and conglomerate range approximately 0 to 0.6. Cross-plots of gamma-ray versus bulk density, acoustic transit time (DT), and AI were employed to estimate various petrophysical parameters of the sandstone. The analysis results (Figure 13) demonstrate that sandstone typically exhibits high-density, low-DT, and high-AI characteristics. Specifically, the AI of sandstone, glutenite, and conglomerate ranges from approximately 5500 to 14,000 (m/s) × (g/cm<sup>3</sup>), whereas mudstone and clay exhibit impedance ranging from approximately 3000 to 5300 (m/s) × (g/cm<sup>3</sup>). Sandstone consistently exhibits higher impedance values compared to mudstone.

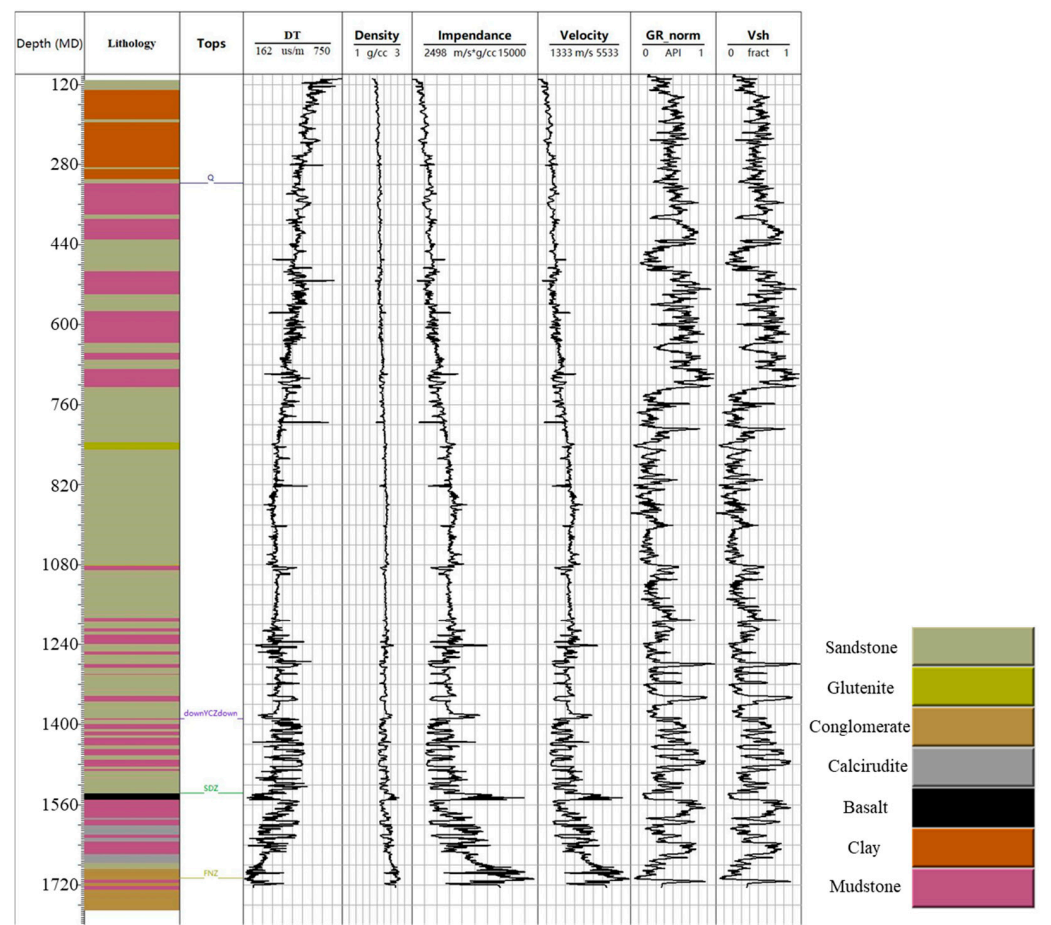
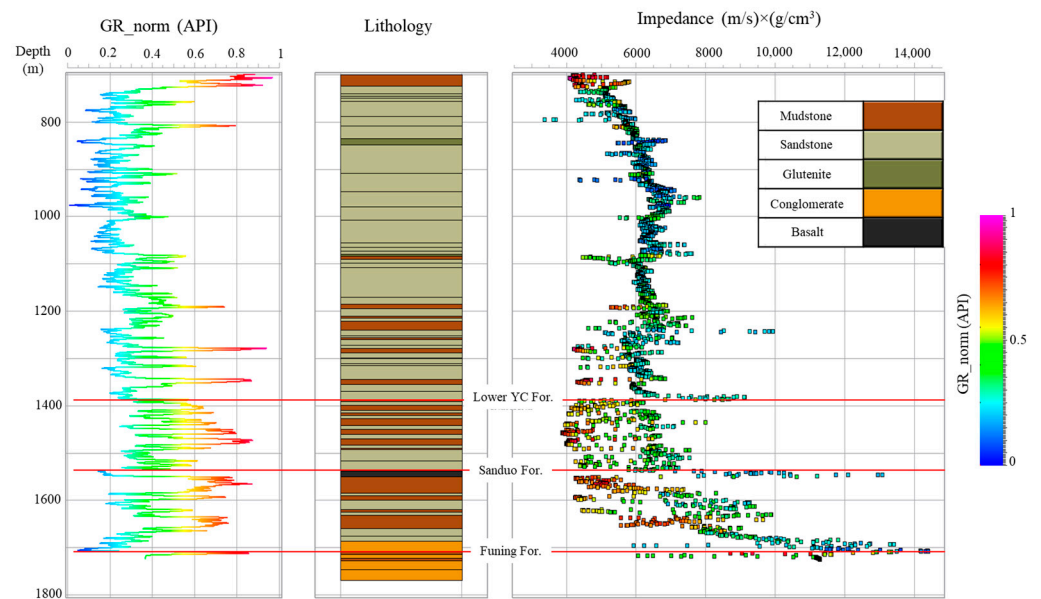
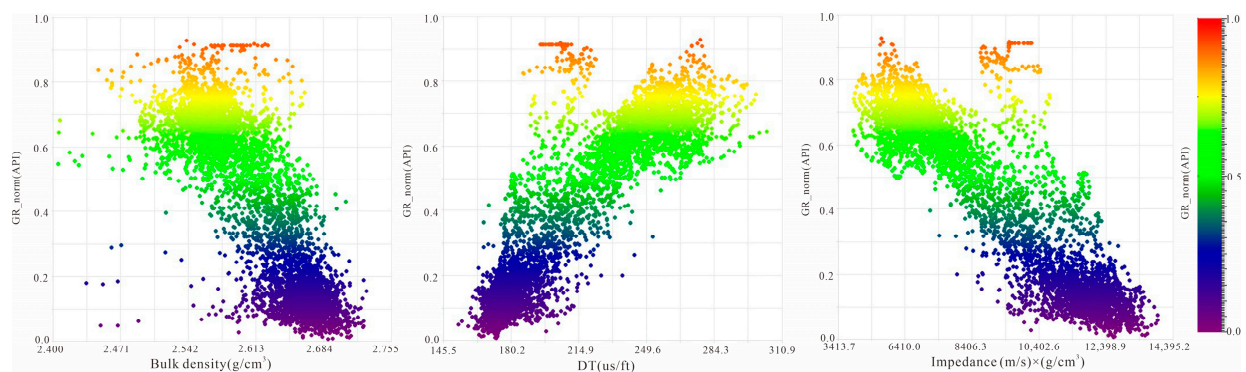


Figure 11. Logging data of well H2 in the Yantai Depression, South Yellow Sea Basin.





**Figure 12.** Analysis of logging data for well H2 in the Yantai Depression, South Yellow Sea Basin, color-coded by gamma-ray.



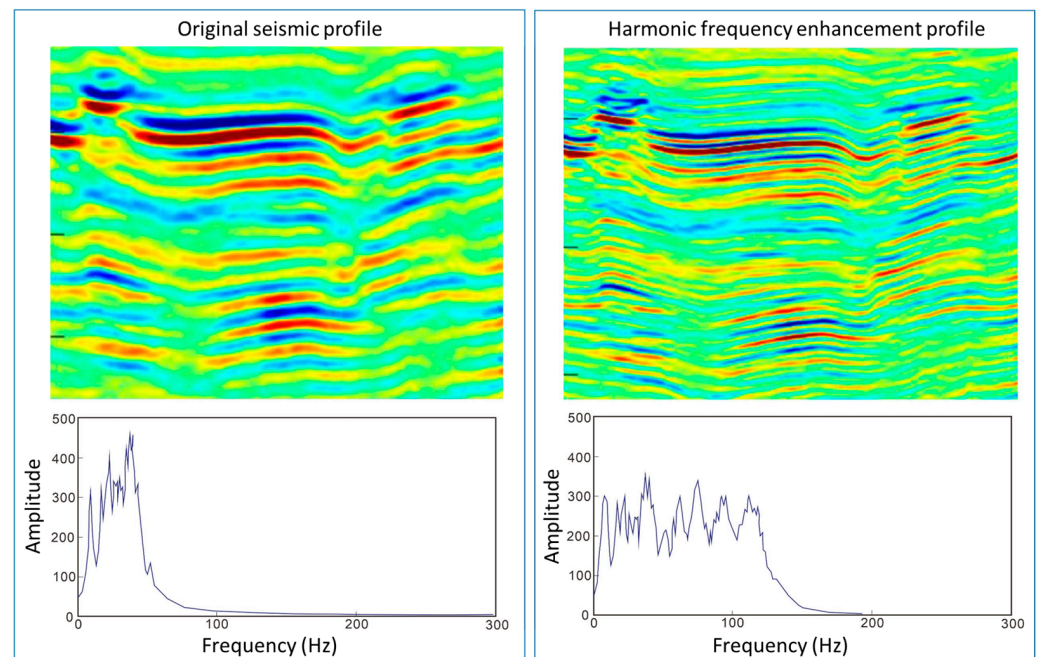
**Figure 13.** Cross-plots of gamma-ray (GR) versus bulk density, DT, and AI of well H2, color-coded by gamma-ray.

#### 4.2.3. Sandstone as Potential CO<sub>2</sub> Storage Reservoirs Derived from Seismic Inversion

AI reflects the continuous variation in subsurface physical properties such as density and velocity, making it an important tool for lithology identification. However, extracting AI from seismic data requires seismic inversion, which involves converting seismic reflection amplitudes into impedance values.

Impedance inversion is highly sensitive to seismic noise. To obtain the most accurate AI data, we applied diffusion filtering, also known as coherence-enhancing anisotropic filtering, to the post-stack data before inversion. This directional smoothing technique excels at noise suppression, lateral continuity improvement, and edge preservation compared to other filtering methods. To further enhance data resolution and better reflect lithological changes in thin layers, we employed a harmonic frequency enhancement algorithm, which increases the frequency of the post-stack data (Figure 14). This technique applies continuous wavelet transform (CWT) time-series analysis to the original seismic record, leveraging the multi-resolution characteristics of the continuous wavelet domain. By calculating the harmonic information of the seismic wavelet (integer multiples of the fundamental frequency) and adding it to the original seismic record, the method broadens the frequency bandwidth and improves the resolution of stratigraphic characterization. This approach

surpasses the limitations of traditional convolution models by expanding both high- and low-frequency information simultaneously.



**Figure 14.** Comparison of harmonic frequency enhancement seismic profile and frequency spectra.

In this study, the colored inversion methodology was employed to invert AI data from seismic post-stack data, as described in Section 3. Applying the matching operator to invert the seismic data produces an AI inversion profile (Figure 15). By analyzing the AI curves of each well, the compaction baselines of pure sandstone and pure mudstone were picked for each well, and then the AI was converted to obtain the percentage content of sandstone using time average formula (Formula (1)), as shown in Figure 16. The inversion results show good consistency with the lithology of the drilling data.

$$\frac{1}{\text{Impedance}} = \frac{1 - V_{\text{sand}}}{\text{Impedance}_{\text{shale}}} + \frac{V_{\text{sand}}}{\text{Impedance}_{\text{sand}}} \quad (1)$$

Here, the variables *Impedance*, *Impedance<sub>shale</sub>*, and *Impedance<sub>sand</sub>* represent the impedance values of actual formation, pure shale, and pure sandstone, respectively. *V<sub>sand</sub>* is the percentage content of sandstone.

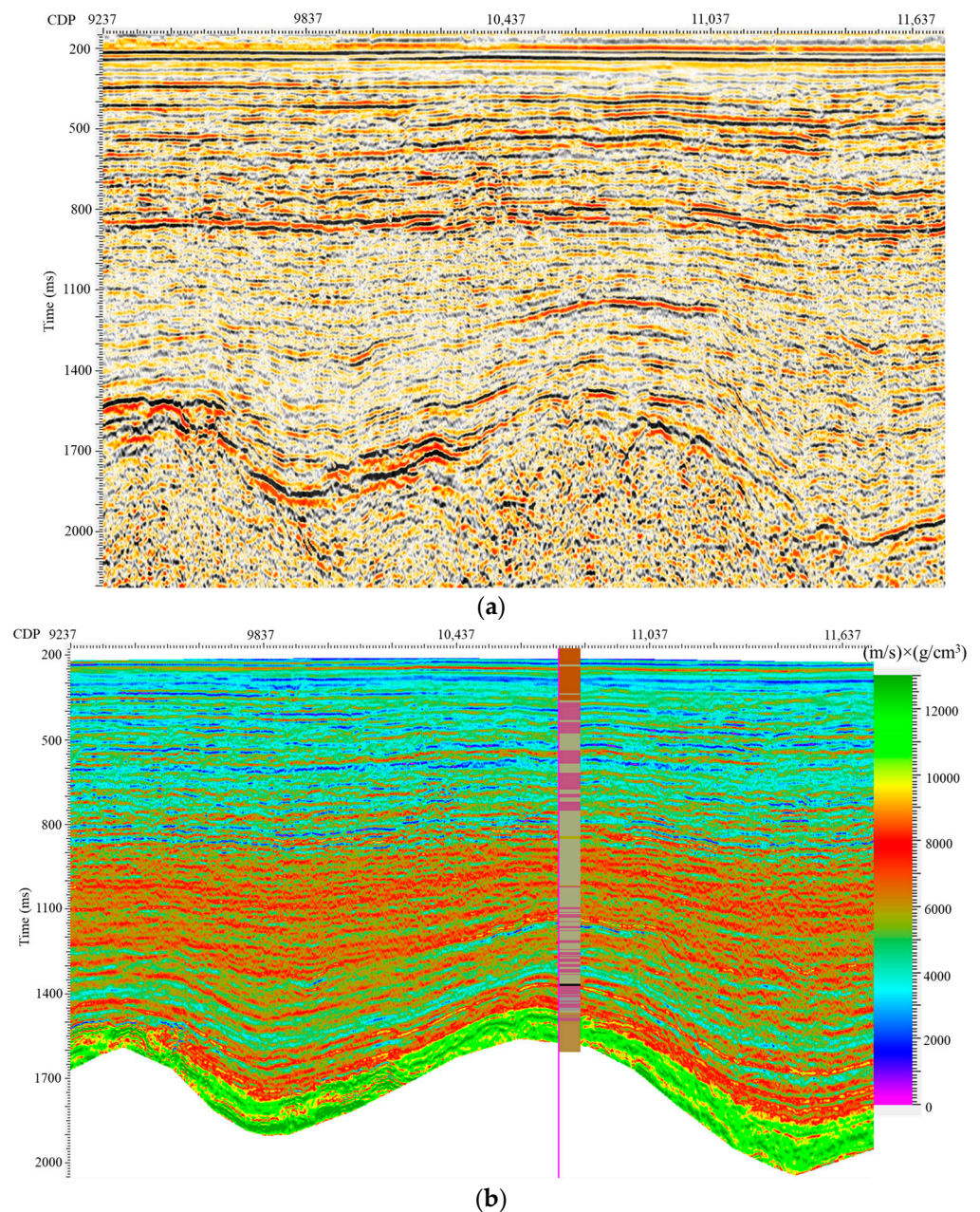
#### 4.2.4. Cenozoic Reservoir Characteristics

Three main sets of reservoirs were developed in the Cenozoic era of the Yantai Depression in the South Yellow Sea Basin: the Funing Formation, Dainan–Sanduo Formation, and Yancheng Formation.

The Funing Formation mainly comprises shallow lacustrine deposits with relatively well-developed sandstone layers. In the northern part of the depression, according to wells H2, ZC1-2-1, and H7, the sandstone layer of the first member of the Funing Formation is 1 to 10 m thick, with the thickest layer reaching about 28 m (Figure 17). The lithology includes feldspathic sandstone and partially tuffaceous sandstone with calcium cementation. The first member of the Funing Formation contains two sections of calcareous fine sandstone at depths of 1565–1568 m and 1586–1587 m, respectively, in well H2. The porosity levels measured from rock samples for these two sections are 19.26% and 13.94%, respectively, with permeability for the first section ranging from 0.27 to 41.40 mD and 1.66 mD for the second section. According to well ZC1-2-1, in the second to fourth members of the Funing Formation, the sandstone is primarily fine siltstone, with single-layer thickness generally

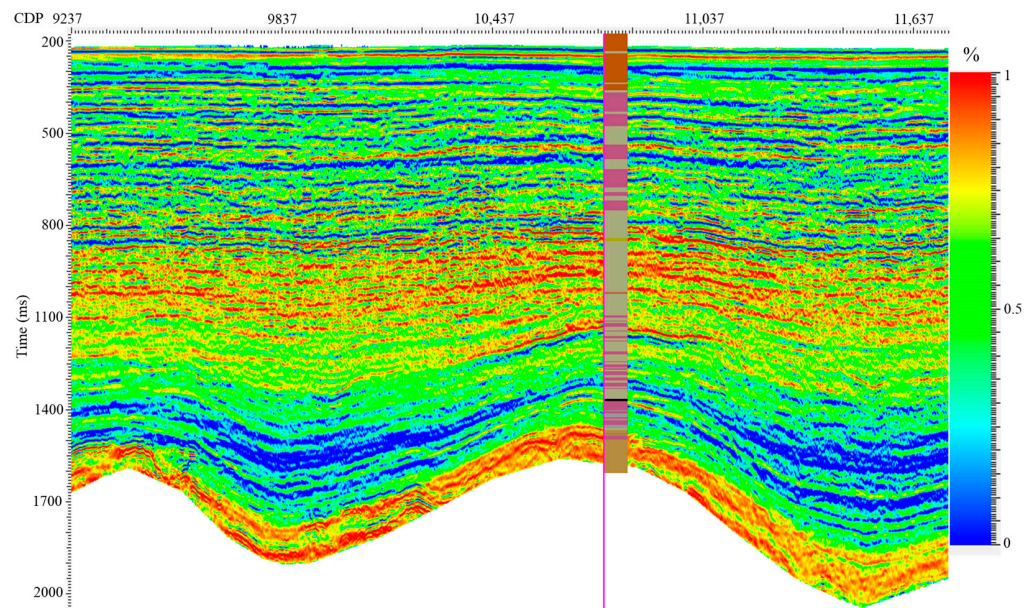


ranging from 1 to 5 m, and the thickest layer reaching 25 m (Figure 18). This sandstone is mainly feldspathic quartz sandstone, with matrix porosity ranging from 26% to 29%, and a maximum of 30.5%. In the southern part of the depression, according to well H5, the sandstone layer is about 1 to 4 m thick, with the thickest layer being 8 m. It is mainly feldspathic sandstone with high rock debris content, as well as calcium and argillaceous cementation. From the perspective of petrophysical properties, the Funing Formation in the northern part of the study area is superior to that in the southern part. This superiority is likely due to the more developed lacustrine deposits in the northern part, characterized by well-sorted and highly mature sedimentary materials. Furthermore, the provenance of sediments is primarily the Qianliyan Uplift, which is dominated by metamorphic rocks, resulting in a high quartz content in the sedimentary deposits.

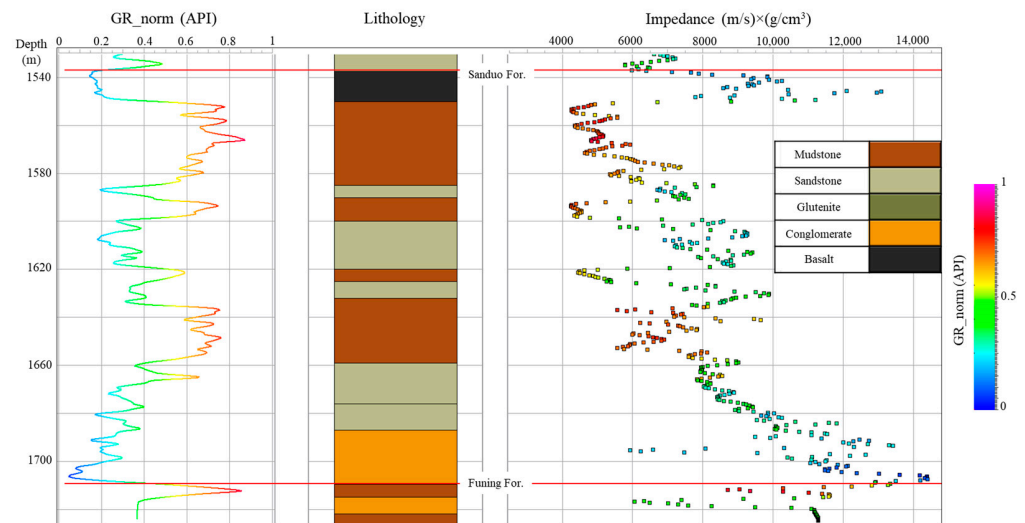


**Figure 15.** An AI inversion result in the Yantai Depression, South Yellow Sea Basin. (a) The seismic profile. (b) The AI inversion profile.



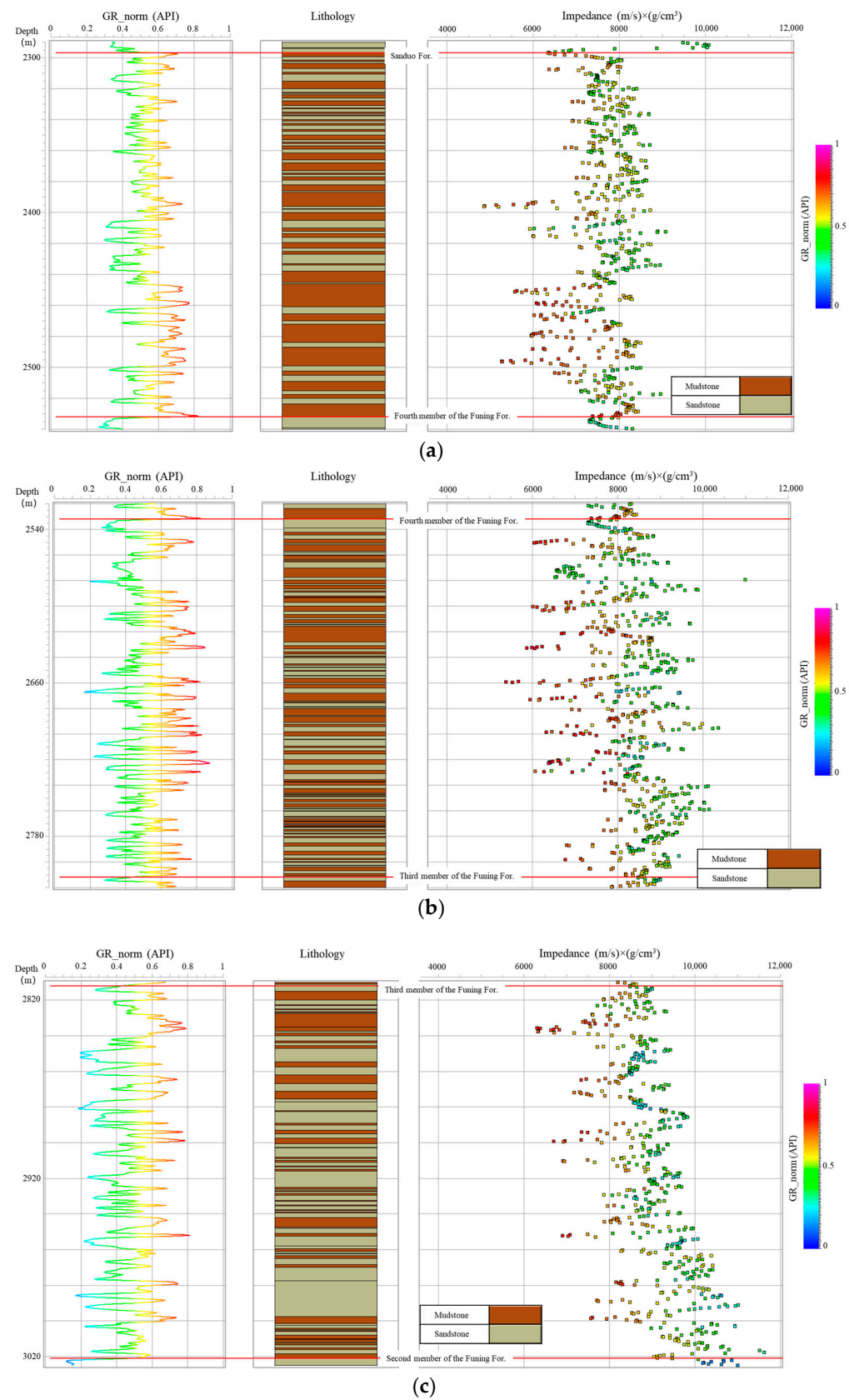


**Figure 16.** The percentage content of sandstone profile in the Yantai Depression, South Yellow Sea Basin.

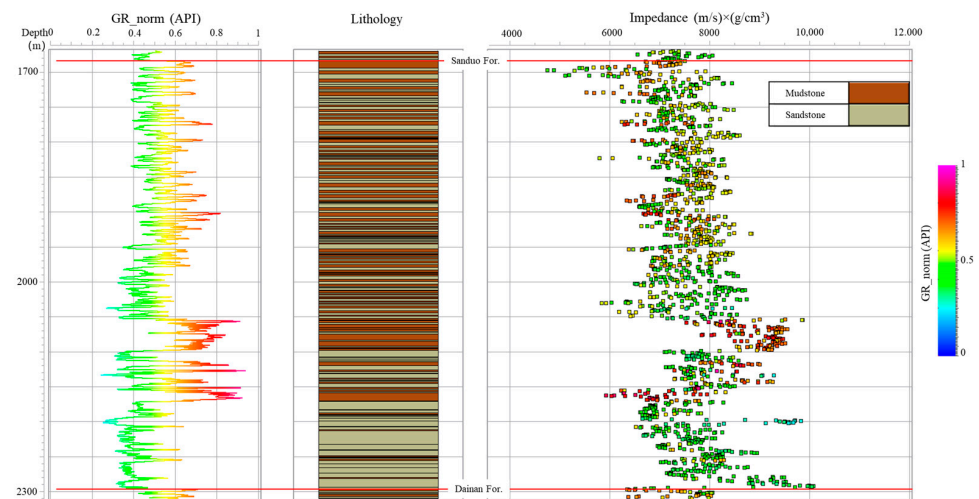


**Figure 17.** Comparison chart of lithological profile, gamma-ray, and impedance curves of the first member of the Funing Formation at well H2. Color-coded by gamma-ray.

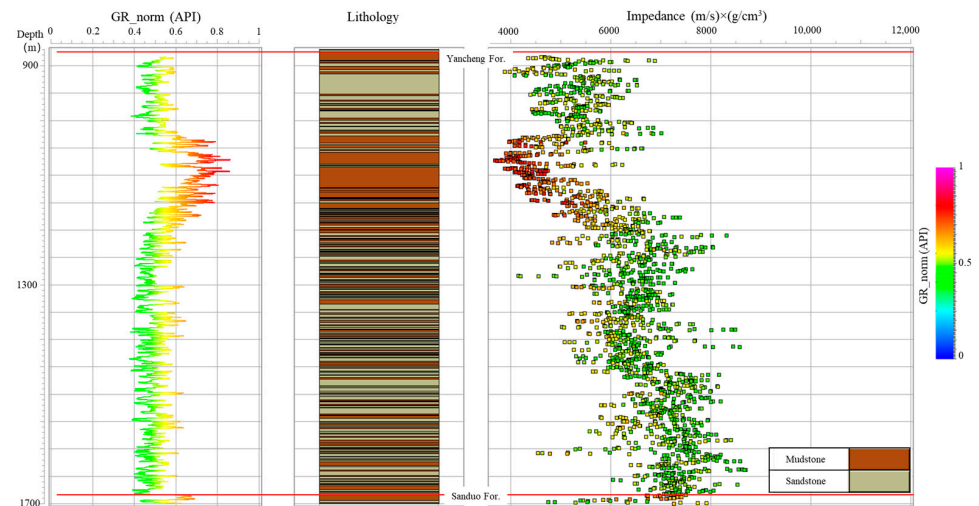
The sandstone of the Sanduo–Dainan Formation is relatively well-developed, with alternating layers of sandstone and shale. It is primarily composed of feldspathic quartz sandstone with muddy cementation and relatively loose texture. According to well ZC1-2-1, the sandstone of the Dainan Formation accounts for 57.2% of the stratigraphic thickness, with single-layer thickness ranging from 5 to 10 m, and a maximum thickness of 19 m (Figure 19). The sandstone thickness of the Sanduo Formation accounts for 57.6% of the stratigraphic thickness, with single layer thickness generally ranging from 5 to 10, with the thickest layer reaching about 37 m (Figure 20). The petrophysical properties are relatively good. According to the tests conducted on six core samples from well ZC1-2-1, the porosity of the Dainan Formation is 7.2%, while the Sanduo Formation ranges from 13.2% to 28.4%, averaging over 20%. The permeability of Sanduo Formation ranges from 0.33 to 60.80 mD, with an average of 27.8 mD, while the permeability of the Dainan Formation ranges from 0.38 to 19.8 mD. From the petrophysical of physical properties, the Sanduo Formation is superior to the Dainan Formation.



**Figure 18.** Comparison chart of lithological profile, gamma-ray, and impedance curves of the first member of the Funing Formation at well ZC1-2-1. Color-coded by gamma-ray. (a) The fourth member of the Funing Formation. (b) The third member of the Funing Formation. (c) The second member of the Funing Formation.



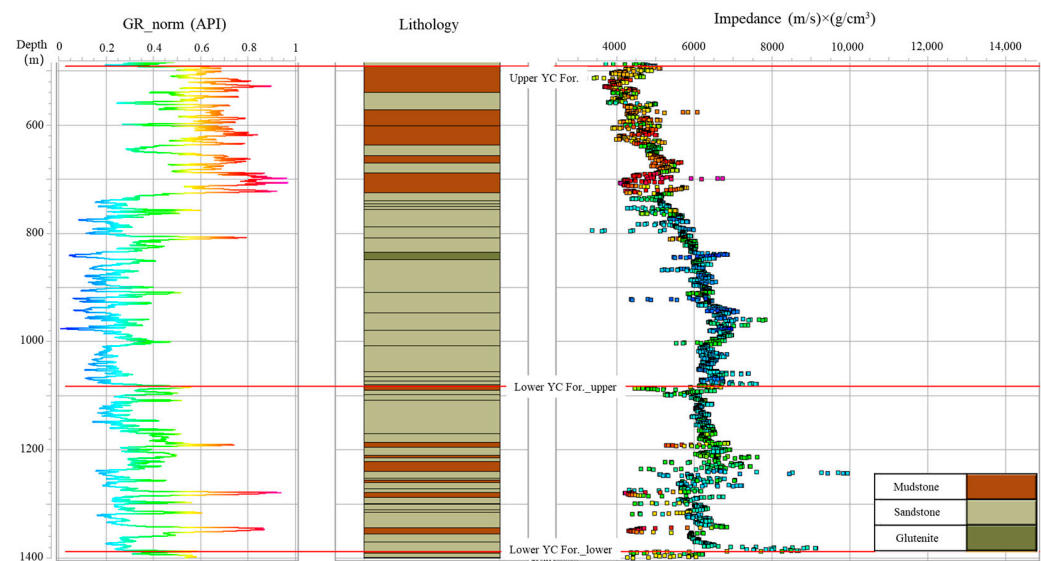
**Figure 19.** Comparison chart of lithological profile, gamma-ray, and impedance curves of the Dainan Formation at well ZC1-2-1. Color-coded by gamma-ray.



**Figure 20.** Comparison chart of lithological profile, gamma-ray, and impedance curves of the Sanduo Formation at well ZC1-2-1. Color-coded by gamma-ray.

Both drilling and seismic inversion results indicate a substantial presence of sandstone in the Yancheng Formation (Figure 14). In the Lower Yancheng Formation, sandstone accounts for 62.5% to 79.8% of the stratum thickness, while in the Upper Yancheng Formation, it ranges from 34% to 54%. According to the well H2, the total thickness of sandstones in the Lower Yancheng Formation is 667.5 m, accounting for 74.5% of the stratum thickness, with the thickest layer more than 200 m (Figure 21), which is similar to the Utsir reservoir of the Spleiner project. According to the sandstone content profile obtained from seismic inversion, the sandstone content is approximately 40% to 80%, with a maximum value of 90%. The sandstone is coarse and unconsolidated, with excellent physical properties. The porosity of siltstone debris from 1321 to 1327 m in well H2 ranges from 24% to 25%, and the permeability is between 9.4 and 216.36 mD. The fluvial sandstone is well-sorted, and due to lateral erosion, it is widely developed, therefore indicating favorable reservoir petrophysical properties in the Yancheng Formation.





**Figure 21.** Comparison chart of lithological profile, gamma-ray, and impedance curves of the Lower Yancheng Formation at well H2. Color-coded by gamma-ray.

Drilling data reveal three sets of thick mudstones in the longitudinal direction of the Yantai Depression that can serve as caprocks. In the third and fourth members of the Funing Formation, mudstone accounts for 80% of the strata, with a maximum accumulated thickness of about 2000 m. The single-layer thickness exceeds 15 m, reaching up to 60 m, indicating good distribution stability. In the Dainan Formation, mudstone comprises 70% of the strata, with a maximum accumulated thickness of 1200 m. In the upper Yancheng Formation, mudstone accounts for 60% of the strata, with single-layer thickness ranging from 5 to 10 m and a maximum thickness of 18 m, demonstrating good continuity and suitability as a regional caprock.

## 5. Discussion

### 5.1. Analysis of the Genesis of Multi-Type Structural Traps

Since the Mesozoic era, the Yantai Depression has experienced multiple tectonic movements, leading to changes in regional stress fields and intense stratigraphic deformation, resulting in various tectonic styles and patterns. The tectonic framework of the South Yellow Sea Basin underwent significant transformation under the influence of the Indosinian–Early Yanshanian orogenic movement [25]. The collision and amalgamation of the North China Plate and the Yangtze Plate created two distinct tectonic systems, one above the other. Before this collision, the dominant tectonic activity was vertical movement. Following the Late Triassic to Early Jurassic collision, the connection with the Paleotethys Ocean was severed, transitioning the region into a terrestrial Mesozoic foreland basin. The Late Jurassic to Early Cretaceous period marked a phase of regional stress field adjustment in the South Yellow Sea Basin, with diminishing compression and thrusting, and increasing strike-slip tension. The Qianliyan Fault transitioned into a syngenetic normal fault, leading the Yantai Depression into a fault-controlled faulted basin.

During the Late Cretaceous, the influence of the Circum-Pacific tectonic domain placed the South Yellow Sea crust in an extensional state, resulting in a tensile environment. This led to the formation of extensive tensile faults and a series of graben or half-graben structures overlying different basements or tectonic units. In the early Paleogene, the Yantai Depression inherited these tensile extension characteristics, with increased fault activities, forming alternating horsts and grabens. The basin continued to subside, accumulating sediment and eventually filling the entire basin. During this period, the combined influence of the Tanlu fault strike-slip movement and the subduction of the Pacific Plate towards the Eurasian Plate caused variations in stress effects between the east and west of the Yantai

Depression, leading to different tectonic patterns. By the end of the Eocene, the subduction direction of the Pacific Plate shifted from NNW to NWW. The Wubu movement primarily involved fault block uplift and downthrow, accompanied by localized compression. The intense faulting activities caused basement tilting, which also affected the underlying fault-sag structural layers, leading to the erosion of the uplifted areas and some slope fault-sag structural layers. In the Oligocene, the intensified subduction of the Pacific Plate in the NWW direction altered the stress field. The Sanduo movement was mainly characterized by intense compression and shear strike-slip activities. The basin rapidly uplifted, forming a series of NW-trending fold structures and thrust faults, while some depressions exhibited strike-slip characteristics. Strongly extruded anticlines were eroded at the top, and the weakly deposited strata were thinned, with Oligocene strata being strongly eroded and mostly missing. The compression and modification movement at the end of the Oligocene concluded the half-graben fault depression development in the South Yellow Sea Basin, transitioning the basin into a regional subsidence stage with significantly reduced fault activities.

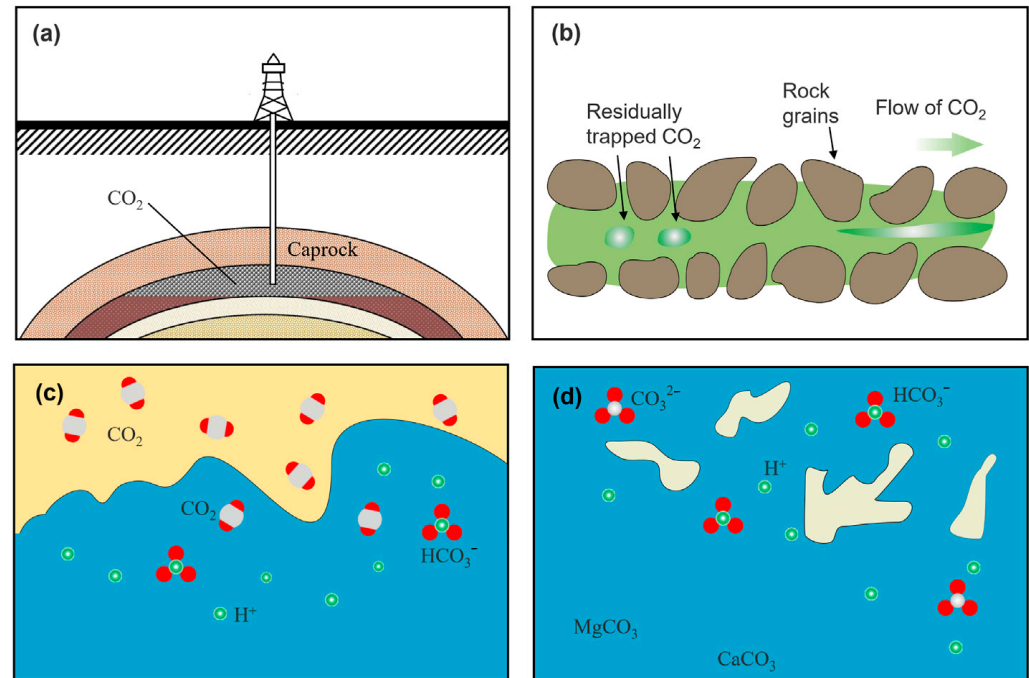
Seismic data reveal that structural traps are the primary trap types in the Yantai Depression, with a total of 60 identified. Among them, 28 (46.7%) are anticlines formed by compressive stress, while 32 (53.3%) are fault blocks and fault anticlines formed by faulting. Consequently, the formation of these structural traps in the Yantai Depression is primarily driven by two factors: lateral compressive stress and fault activities. There are 13 anticlines, mainly including thrust and compressional type, formed by the regional compressive stress. It is speculated that this stress was generated due to changes in the direction of plate subduction, driven by the eastward movement of the Pacific Plate during the late Eocene and Oligocene epochs. Therefore, the formation of this structure is relatively late, around the Sanduo movement period of the Paleogene. The relatively strong regional stress field often led to the folding deformation of both the Paleogene strata and the underlying basement. Another type of anticline is the collapse anticlines, formed by local compressive stress, and there are 16 of this type in total. It is hypothesized that the lateral compressive stress for the collapse anticlines originated from the paleo-uplift of the Laoshan Uplift during the Paleogene period, causing adjacent muddy rock bodies to slide and collapse along the dip direction, forming fold anticlines. Such structures typically only cause structural deformation in part of the Paleogene strata, while the basement retains its original shape. These structures are primarily formed from the end of the Eocene to the end of the Oligocene, and they are mainly distributed in regions closely adjacent to the Laoshan Uplift. In addition, extensional forces during the Late Cretaceous to Early Paleogene period resulted in the formation of numerous normal faults, giving rise to fault block structures primarily distributed along slopes and of relatively small scale. When the downthrown block of these faults was subjected to compression from the Sanduo movement, fault anticlines formed, predominantly located at the edges of the depressions.

## 5.2. Significance of Structural Traps for Geological Storage of CO<sub>2</sub>

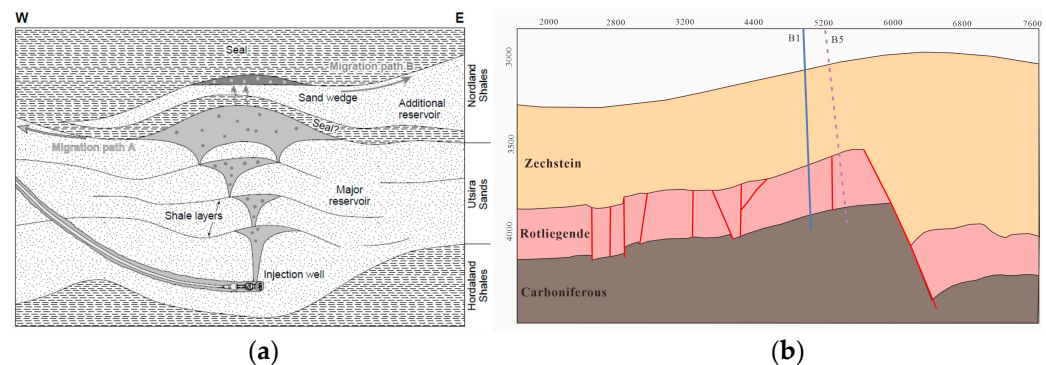
The mechanisms of CO<sub>2</sub> storage in saline aquifers include structural, residual, solubility, and mineral trapping (Figure 22) [11]. Structural trapping involves injecting CO<sub>2</sub> into the reservoir space of a structure trap, where the dense caprock above prevents the upward migration of CO<sub>2</sub> due to buoyancy, thereby achieving effective geological storage. This method is favored for its large storage capacity, good stability, and relatively straightforward implementation [14,15].

Structural traps play a vital role in the geological storage of CO<sub>2</sub> [22]. These traps effectively prevent CO<sub>2</sub> from migrating upward and escaping into the atmosphere, ensuring the stability and safety of long-term storage. Globally, typical offshore geological storage projects often utilize structural trap. For instance, the Sleipner project in Norway, the world's first megaton-scale CO<sub>2</sub> geological storage project in deep saline aquifers [14], employs an anticlinal trap [36] as the main storage space (Figure 23a). Anticlinal traps are preferred for large-scale CO<sub>2</sub> geological storage projects due to their simple structures, large

storage capacity, and high safety. Similarly, fault block traps are significant sites for offshore CO<sub>2</sub> storage. Notable examples include the Snohvit project in Norway, the Tomakomai project in Japan, the Gorgon project in Australia, and the K12-B project in the Netherlands (Figure 23b), all of which use fault block traps as their primary storage space for CO<sub>2</sub>.



**Figure 22.** Four types trapping mechanisms of CO<sub>2</sub> storage in saline aquifers [11]: (a) structural trapping; (b) residual trapping; (c) solubility trapping; (d) mineral trapping.



**Figure 23.** Geological concept model of the CO<sub>2</sub> storage site of two typical projects. (a) The Sleipner project [36]. (b) The K12-B project [37].

The complexity of tectonic movements in the Yantai Depression have led to the formation of various structural traps, which can provide effective storage spaces for CO<sub>2</sub> geological storage, offering a large capacity that is conducive to long-term and stable CO<sub>2</sub> sequestration. All types of anticline traps discussed in the paper can serve as candidates for CO<sub>2</sub> geological storage site selection. Among them, compressional anticlines, characterized by relatively stable stratigraphic structures and a lack of fault activities, could significantly reduce the risk of CO<sub>2</sub> leakage during sequestration, thus ensuring long-term safety. This makes them the preferred option for large-scale, cost-effective carbon sequestration projects. Although fault-related structural traps, such as faulted anticlines and fault blocks, can also serve as storage spaces for CO<sub>2</sub>, exemplified by the tilted fault block structure of the Netherlands' K12-B project (Figure 23b), the faulted anticline structure of the German



Ketzin project, and the Alpha and Beta structures of the Norwegian Smeaheia project, the stability evaluation of faults during site selection is crucial. Analyzing the fault activation mechanism, having a good understanding of the injection-induced deformation and associated integrity issues, and clarifying the appropriate CO<sub>2</sub> injection method can ensure long-term stable storage. Overall, these structural traps in the Yantai Depression are of great significance for reducing CO<sub>2</sub> emissions in the coastal regions of Shandong and Jiangsu provinces, contributing to efforts to mitigate global climate change.

### 5.3. Analysis of the Reservoir–Caprock Combination

Based on the analysis of reservoirs and caprocks, the Yantai Depression exhibits four primary reservoir–caprock combinations: (1) a high-quality Lower Yancheng Formation reservoir paired with the overlying Upper Yancheng mudstone, (2) fluvial sandstone of the Sanduo Formation coupled with overlying mudstone, (3) a Dainan–Sanduo Formation combination, and (4) an internal Funing Formation combination. From a sedimentary sequence standpoint, the Funing Formation's multiple normal cycles, with coarse lower and fine upper parts representing alternating shore-shallow lacustrine, fluvial, and deep-semi-deep lacustrine facies, render its internal reservoir–caprock combination a better choice in the study area. Conversely, in terms of reservoir characteristics, the Lower Yancheng Formation stands for having the thickness of sandstone layers, accompanied by favorable physical properties and relatively shallow burial depths, typically ranging from 800 to 1500 m. Furthermore, its simple geological structure, combined with stable and continuous caprocks, makes it the preferred reservoir for CO<sub>2</sub> geological sequestration in the Yantai Depression.

## 6. Conclusions

The relatively complex tectonic movements in the Yantai Depression have led to diverse structural styles and local structures, resulting in various types of structural traps, including trust anticlines, collapsed anticlines, compressional anticlines, faulted anticlines, and fault blocks. Among these, the compressive anticline is particularly well-suited for CO<sub>2</sub> geological storage. However, the faults in the Yantai Depression are relatively developed. On the one hand, fault activity can form structural traps such as fault anticlines or fault blocks, which can block the injected CO<sub>2</sub>. On the other hand, it can also increase the risk of CO<sub>2</sub> leakage. Therefore, a thorough stability evaluation of faults during site selection is crucial. Understanding fault activation mechanisms, assessing injection-induced deformation and associated integrity issues, and clarifying the most appropriate CO<sub>2</sub> injection methods are crucial for ensuring long-term storage stability.

Based on the analysis of reservoirs and caprocks, the Yantai Depression exhibits four primary reservoir–caprock combinations: (1) a high-quality Lower Yancheng Formation reservoir paired with the overlying Upper Yancheng mudstone, (2) fluvial sandstone of the Sanduo Formation coupled with overlying mudstone, (3) a Dainan–Sanduo Formation combination, and (4) an internal Funing Formation combination. The Lower Yancheng Formation is particularly promising, as it features thick sandstone layers with favorable petrophysical properties and relatively shallow burial depths (typically 800 to 1500 m). From the reservoir characteristics standpoint, the Lower Yancheng Formation stands for having the thickness of sandstone layers, accompanied by favorable physical properties and relatively shallow burial depths, typically ranging from 800 to 1500 m. Furthermore, its simple geological structure, combined with stable and continuous caprocks, makes it the preferred reservoir for CO<sub>2</sub> geological storage in the Yantai Depression. The favorable structural traps and reservoir–caprock conditions provide feasibility for the CO<sub>2</sub> geological storage in the Yantai Depression. However, selection for candidate sites in this area still faces significant challenges. Firstly, the detailed quantitative evaluation is necessary. Current, this work is in progress, utilizing petrophysical analysis and seismic inversion to achieve quantitative characterization of the reservoir–caprock layers, aiming to obtain additional petrophysical parameters such as porosity and permeability. Due to the absence

of pre-stack seismic data, we cannot derive additional seismic elastic parameters, including shear wave velocity and the P-wave to S-wave velocity ratio ( $V_p/V_s$ ) through seismic inversion. Consequently, we are limited in characterizing the rock mechanical properties of the reservoir and caprock layers based on seismic data. To overcome this limitation, further seismic exploration in the Yantai Depression is currently being planned and will be implemented accordingly. Secondly, stability evaluation is crucial. By using numerical simulations and physical modeling, we aim to understand the migration patterns of  $\text{CO}_2$  within the reservoir and evaluate the safety and stability of the storage. This will provide important evidence for selecting optimal  $\text{CO}_2$  storage sites and the implementing engineering strategies in the Yantai Depression.

**Author Contributions:** Conceptualization, D.L., Y.Y. and J.C.; methodology, D.L.; validation, D.L. and Q.L.; formal analysis, J.L. and Q.L.; investigation, J.L.; data curation, H.Z.; writing—original draft preparation, D.L.; writing—review and editing, Y.Y., D.L.; supervision, Y.Y.; project administration, J.C.; funding acquisition, J.C., Y.Y. All authors have read and agreed to the published version of the manuscript.

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## References

- Bredesen, K. Assessing rock physics and seismic characteristics of the Gassum Formation in the Stenlille aquifer gas storage—A reservoir analog for the Havnsø  $\text{CO}_2$  storage prospect, Denmark. *Int. J. Greenh. Gas Control*. **2022**, *114*, 103583. [\[CrossRef\]](#)
- Delanoë, P.; Tchuente, D.; Colin, G. Method and evaluations of the effective gain of artificial intelligence models for reducing  $\text{CO}_2$  emissions. *J. Environ. Manag.* **2023**, *331*, 117261. [\[CrossRef\]](#) [\[PubMed\]](#)
- Saidi, K.; Omri, A. Reducing  $\text{CO}_2$  emissions in OECD countries: Do renewable and nuclear energy matter? *Prog. Nucl. Energy* **2020**, *126*, 103425. [\[CrossRef\]](#)
- Um, E.S.; Alumbaugh, D.; Commer, M.; Feng, S.; Gasperikova, E.; Li, Y.; Lin, Y.; Samarasinghe, S. Deep learning multiphysics network for imaging  $\text{CO}_2$  saturation and estimating uncertainty in geological carbon storage. *Geophys. Prospect.* **2024**, *72*, 183–198. [\[CrossRef\]](#)
- Lauk, C.; Kaufmann, L.; Theurl, M.C.; Wittmann, F.; Eder, M.; Hrtenhuber, S.; Freyer, B.; Krausmann, F. Demand side options to reduce greenhouse gas emissions and the land footprint of urban food systems: A scenario analysis for the City of Vienna. *J. Clean. Prod.* **2022**, *359*, 132064. [\[CrossRef\]](#)
- Zhang, Y.; Smith, S.J.; Bowden, J.H.; Adelman, Z.; West, J.J. Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050. *Environ. Res. Lett.* **2017**, *12*, 114033. [\[CrossRef\]](#)
- Chen, L.; Msigwa, G.; Yang, M.; Osman, A.I. Strategies to achieve a carbon neutral society: A review. *Environ. Chem. Lett.* **2022**, *20*, 2277–2310. [\[CrossRef\]](#)
- Zhao, X.; Ma, X.; Chen, B.; Shang, Y.; Song, M. Challenges toward carbon neutrality in China: Strategies and countermeasures. *Resour. Conserv. Recycl.* **2022**, *176*, 105959. [\[CrossRef\]](#)
- Liu, Z.; Gao, M.; Zhang, X.; Liang, Y.; Guo, Y.; Liu, W.; Bao, J. CCUS and  $\text{CO}_2$  injection field application in abroad and China: Status and progress. *Geoenergy Sci. Eng.* **2023**, *229*, 212011. [\[CrossRef\]](#)
- Nath, F.; Mahmood, M.N.; Yousuf, N. Recent advances in CCUS: A critical review on technologies, regulatory aspects and economics. *Geoenergy Sci. Eng.* **2024**, *238*, 212726. [\[CrossRef\]](#)
- Luo, J.; Xie, Y.; Hou, M.Z.; Xiong, Y.; Wu, X.; Lüddecke, C.T.; Huang, L. Advances in subsea carbon dioxide utilization and storage. *Energy Rev.* **2023**, *2*, 100016. [\[CrossRef\]](#)
- Durucan, S.; Shi, J.-Q.; Sinayuc, C.; Korre, A. In Salah  $\text{CO}_2$  storage JIP: Carbon dioxide plume extension around KB-502 well—New insights into reservoir behaviour at the In Salah storage site. *Energy Procedia* **2011**, *4*, 3379–3385. [\[CrossRef\]](#)
- Martens, S.; Kempka, T.; Liebscher, A.; Lüth, S.; Müller, F. Europe's longest-operating on-shore  $\text{CO}_2$  storage site at Ketzin, Germany: A progress report after three years of injection. *Environ. Earth Sci.* **2012**, *67*, 323–334. [\[CrossRef\]](#)

14. Furre, A.-K.; Eiken, O.; Alnes, H.; Vevatne, J.N.; Kiær, A.F. 20 Years of Monitoring CO<sub>2</sub>-injection at Sleipner. *Energy Procedia* **2017**, *114*, 3916–3926. [\[CrossRef\]](#)
15. Sawada, Y.; Tanaka, J.; Suzuki, C.; Tanase, D.; Tanaka, Y. Tomakomai CCS Demonstration Project of Japan, CO<sub>2</sub> Injection in Progress. *Energy Procedia* **2018**, *154*, 3–8. [\[CrossRef\]](#)
16. Van der Meer, B.L.; Arts, R.J.; Geel, C.R.; Hofstee, C.; Winthagen, P.; Hartman, J.; D'hoore, D. K12-B: Carbon Dioxide Injection in a Nearly Depleted Gas Field Offshore the Netherlands. In Proceedings of the 71st EAGE Conference & Exhibition, Amsterdam, The Netherlands, 8–11 June 2009.
17. Stevens, S.H.; Kuuskraa, V.A.; Gale, J.; Beecy, D. CO<sub>2</sub> Injection and Sequestration in Depleted Oil and Gas Fields and Deep Coal Seams: Worldwide Potential and Costs. *Environ. Geosci.* **2001**, *8*, 200–209. [\[CrossRef\]](#)
18. Wang, Y.; Morozov, I.B. Time-lapse acoustic impedance variations during CO<sub>2</sub> injection in Weyburn oilfield, Canada. *Geophysics* **2019**, *85*, M1–M13. [\[CrossRef\]](#)
19. Guan, Y.; Shan, Y.; Huang, Q.; Chen, H.; Wang, D.; Hubacek, K. Assessment to China's Recent Emission Pattern Shifts. *Earth's Future* **2021**, *9*, e2021EF002241. [\[CrossRef\]](#)
20. Shan, Y.; Huang, Q.; Guan, D.; Hubacek, K. China CO<sub>2</sub> emission accounts 2016–2017. *Sci. Data* **2020**, *7*, 54. [\[CrossRef\]](#)
21. Yuan, Y.; Wang, J.; Chen, J.; Cao, K.; Liang, J.; Lan, T.; Lu, D.; Guo, X. Carbon Dioxide Storage Potential of Cenozoic Saline Aquifers in the South Yellow Sea Basin. *Energies* **2023**, *16*, 1578. [\[CrossRef\]](#)
22. Osmond, J.L.; Mulrooney, M.J.; Holden, N.; Skurtveit, E.; Faleide, J.I.; Braathen, A. Structural traps and seals for expanding CO<sub>2</sub> storage in the northern Horda Platform, North Sea. *AAPG Bull.* **2021**, *106*, 1711–1752. [\[CrossRef\]](#)
23. Chen, J.; Lei, B.; Liang, J.; Zhang, Y.; Wu, S.; Shi, J.; Wang, J.; Yuan, Y.; Zhang, Y.; Li, G. New progress of petroleum resources survey in South Yellow Sea basin. *Mar. Geol. Quat. Geol.* **2018**, *38*, 1–23. [\[CrossRef\]](#)
24. Zhang, P.; Huang, H.-H.M.; Hong, Y.; Tian, S.Y.; Liu, J.; Lee, Y.I.; Chen, J.; Liang, J.; Wang, H.; Yasuhara, M. Southward Migration of Arctic Ocean Species During the Last Glacial Period. *Geophys. Res. Lett.* **2022**, *49*, e2022GL100818. [\[CrossRef\]](#)
25. Fu, Y.; Yan, B.; Liang, J. Influence of basement high and detachment on the kinematics of a fold-and-thrust belt in the central South Yellow Sea Basin, China: Insights from analog modeling. *Mar. Pet. Geol.* **2024**, *160*, 106648. [\[CrossRef\]](#)
26. Chen, J.; Liang, J.; Zhang, Y.; Yang, C.; Yuan, Y.; Ming, X.U.; Jianqiang, W.; Baohua, L.; Gan, L.I.; Yanqiu, Y. Regional evaluation of oil and gas resources in offshore China and exploration of marine Paleo-Mesozoic oil and gas in the Yellow Sea and East China Sea. *Mar. Geol. Quat. Geol.* **2019**, *39*, 1–29. [\[CrossRef\]](#)
27. Yuan, Y.; Chen, J.; Liang, J.; Xu, M.; Lei, B.; Zhang, Y.; Cheng, Q.; Wang, J. Hydrocarbon Geological Conditions and Exploration Potential of Mesozoic–Paleozoic Marine Strata in the South Yellow Sea Basin. *J. Ocean. Univ. China* **2019**, *18*, 1329–1343. [\[CrossRef\]](#)
28. Qu, X. *Sedimentary Characteristics and Oil and Gas Prospect for the Mesozoic and Cenozoic in Northern South Yellow Sea Basin*; Jilin University: Changchun, China, 2004.
29. Wu, S. A Systematic Study of the Chinese Petroliferous Basins. *Acta Pet. Sin.* **1993**, *14*, 20–34. [\[CrossRef\]](#)
30. Li, X.; Liu, S.; Wang, L. Spatiotemporal Pattern of Earthquake Activities and Seismotectonics in Jiangsu and Adjacent Southern Yellow Sea Area. *Geol. J. China Univ.* **2018**, *24*, 551.
31. Li, X.; Wei, N.; Liu, Y.; Fang, Z.; Dahowski, R.T.; Davidson, C.L. CO<sub>2</sub> Point Emission and Geological Storage Capacity in China. *Energy Procedia* **2009**, *1*, 2793–2800. [\[CrossRef\]](#)
32. Huo, C. *Study on the Potential Evaluation and the Storage Areas of the Carbon Dioxide Seabed Storage in Offshore China*; Dalian Maritime University: Dalian, China, 2014.
33. Gardner, G.H.F.; Gardner, L.W.; Gregory, A.R. Formation velocity and density; the diagnostic basics for stratigraphic traps. *Geophysics* **1974**, *39*, 770–780. [\[CrossRef\]](#)
34. Asquith, G.B.; Krygowski, D. *Basic Well Log Analysis*; American Association of Petroleum Geologists: Tulsa, OK, USA, 2004; Volume 16.
35. Lancaster, S.; Whitcombe, D. Fast-track 'coloured' inversion. In *SEG Technical Program Expanded Abstracts 2000*; SEG: Houston, TX, USA, 2020; pp. 1572–1575.
36. Zweigel, P.; Hamborg, M.; Arts, A.E. Prediction of migration of CO<sub>2</sub> injected into an underground depository: Reservoir geology and migration modelling in the Sleipner case (North Sea). In *Greenhouse Gas Control Technologies: Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies*; CSIRO Publishing: Clayton, Australia, 2000.
37. Audigane, P.; Lions, J.; Gaus, I.; Robelin, C.; Durst, P.; Van der Meer, B.; Geel, K.; Oldenburg, C.M.; Xu, T. Geochemical modeling of CO<sub>2</sub> injection into a methane gas reservoir at the K12-B field, North Sea. In *Carbon Dioxide Sequestration in Geological Media—State of the Science*; American Association of Petroleum Geologists: Tulsa, OK, USA, 2009.

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