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Advances in Offshore Oil and Gas Exploration and Development

Edited by
Mianmo Meng, Wenming Ji and Guodong Cui

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Advances in Offshore Oil and Gas Exploration and Development

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Advances in Offshore Oil and Gas Exploration and Development

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Oceans cover nearly 71% of the Earth's surface, and their underlying sedimentary strata hold vast oil and gas reserves that can alleviate global energy shortages. However, extracting these resources remains highly challenging. On the one hand, the marine environment is complex and harsh, subjecting operations to extreme conditions, such as high pressure, low temperatures, strong ocean currents, and severe corrosion [1,2]. On the other hand, offshore oil and gas development demands highly advanced technological capabilities, facing significant hurdles in high-precision seismic-reflection survey, deep-water drilling, as well as oil and gas transportation [3,4]. Simultaneously, unconventional oil and gas have become increasingly vital to the petroleum industry, necessitating further investigation and research [5–7].

Contribution 1 detailed the accumulation mechanisms of uranium (U) and thorium (Th) in the marine sediments of the Doushantuo Formation shales. The results indicated that U accumulation is primarily controlled by the adsorption and complexation of organic matter (OM), while Th enrichment is governed by the adsorption capacity of clay minerals, providing a scientific basis for regional helium exploration.

Contribution 2 discussed the sedimentary distribution, evolutionary patterns, and hydrocarbon control mechanisms of two phases of Lower Cretaceous source rocks in the Northern Persian Gulf. It was found that source rock quality is synergistically regulated by sedimentary facies and terrestrial input, and the depositional sequences align closely with global anoxic events and marine transgressions.

Contribution 3 investigated the development characteristics of natural fractures in the metamorphic basement reservoirs of the Bozhong Depression. These reservoirs underwent multistage structural evolution and predominantly developed tectonic fractures. Natural fractures of various scales promote the development of large-scale effective reservoirs.

Contribution 4 clarified the genesis of pore structure characteristics in the low-permeability sandstone reservoirs of the Eocene Wenchang Formation, Huizhou Sag. By classifying pore-throat types and assessing their impact on physical properties of reservoirs, this study pointed out that the Wenchang Formation exhibits a “high storage but low production”, suggesting that connected intergranular and dissolution pores are the critical determinants of effective permeability.

Contribution 5 focused on the source-to-sink system analysis of the steep-slope zone in the Wushi Sag, Beibuwan Basin. Through a comparison of migratory and progradational fans, the study indicated that migratory fans possess excellent physical properties and oil-bearing capacity, and subsequently established high-quality reservoir prediction models for both fan types.

Contribution 6 appraised the impact of submarine methane-rich fluids on gas hydrate production during depressurization. The research showed that fluid invasion exerts a

three-phase effect on gas dynamics, characterized by minimal initial impact, intermediate inhibition, and significant late-stage enhancement and demonstrates a notable “1 + 1 > 2” synergistic effect under low rates of water or methane invasion. These findings provide critical guidance for optimizing hydrate recovery strategies.

Contribution 7 proposed a dual-stage attention-based recurrent neural network prediction model to accurately estimate the remaining useful life of offshore electric submersible pumps (ESPs). This method not only improves prediction accuracy but also mitigates equipment degradation through the optimization of operating parameters, thereby enhancing the reliability and economic efficiency of offshore oil production.

Contribution 8 introduced complex nanofluid dispersions (CNDs) as a fracturing fluid additive to enhance oil recovery in tight offshore reservoirs. By reversing rock wettability and reducing flow resistance, CNDs significantly improved spontaneous imbibition recovery, with field applications confirming its substantial potential for production enhancement.

Contribution 9 presented a conceptual model linking the paleohydrology of a marginal sea lacustrine basin to astronomically forced climate variability. This research emphasized the combined roles of obliquity and eccentricity in regulating the hydroclimate of marginal-marine nearshore environments, which ultimately imprints on the distribution of shale-oil sweet spots.

Contribution 10 clarified the biological assemblage patterns of source rocks in the Basal Silurian Renheqiao Formation of Western Yunnan, China. It was found that organic matter enrichment is controlled by primary producers, whereas the presence of secondary consumers like graptolites is detrimental to accumulation.

Contribution 11 analyzed the strike-slip activity of the Tinjar–West Baram Fault (TWBF) in the southern South China Sea through 2D seismic profile analysis. This research pointed out that the displacement along the TWBF significantly controlled the deep-water sedimentary systems of the Zengmu Basin, which led to a unique “southern oil–northern gas” distribution pattern and diverse trap types.

Contribution 12 investigated the tectonic control on intrabasinal “source-to-sink” systems. It was found that the activity of Fault 3 dominated the paleogeomorphic evolution of the Weixinan Low Uplift and its surrounding areas.

Given the coexistence of potential and challenges, more research should be done to efficiently develop offshore oil and gas. Simultaneously, more attention should be paid to unconventional oil and gas development because conventional oil and gas cannot meet energy consumption requirements associated with the rapid development of the world economy.

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Article

Mechanisms of Uranium and Thorium Accumulation in the Lower Ediacaran Marine Sediments from the Upper Yangtze Platform, China: Implications for Helium Exploration

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Abstract: The ocean is a significant global reservoir of uranium (U) and thorium (Th). These elements can be incorporated into marine sediments through processes involving organic matter (OM), redox conditions, terrigenous inputs, and mineral interactions. Helium generated through the radioactive decay of U and Th within geological formations represents a critical potential resource. Marine black shales, which are rich in U and Th, are widespread in the Ediacaran Doushantuo Formation of the Upper Yangtze Platform, making them a key target for helium exploration. However, there is limited research on the mechanisms behind U and Th accumulation in these shales. This study focuses on shales from the Doushantuo Formation in Chongqing, China, aiming to explore the mechanisms of U and Th accumulation and assess the potential for helium generation, and argillaceous dolomites are included for comparative analysis. The results show that the average U and Th content in the black shales (17.58 and 9.78 ppm, respectively) is higher than that of argillaceous dolomites (3.52 and 2.75 ppm, respectively). Uranium mainly comes from authigenic precipitation and hydrothermal inputs, while thorium is primarily sourced from terrigenous and hydrothermal inputs. The semi-humid climate in the provenance area facilitated parent rock weathering, with atmospheric precipitation and river systems transporting U and Th to the ocean. However, excessive terrigenous input can dilute the U and Th content in the sediments. In the shales, uranium is primarily adsorbed and/or complexed by organic matter (OM), with the anoxic–euxinic sedimentary environment and high OM content (TOC = 0.06–34.58 wt.%, $r = 0.95$) promoting U accumulation. Thorium accumulation is largely controlled by adsorption onto clay minerals. The total amount of helium generated from the Doushantuo shales is estimated to be $7.20 \times 10^{10} \text{ m}^3$.

Keywords: helium exploration; uranium accumulation; thorium accumulation; marine black shales; Ediacaran; Doushantuo formation

1. Introduction

The ocean is one of the largest reservoirs of uranium (U) and thorium (Th) on Earth, with an estimated total amount in the billions of tons, far exceeding the known reserves of these elements on land [1]. The concentrations of U and Th in seawater have remained relatively stable, with U levels typically around 3 ppb (parts per billion) and Th concentrations ranging between 0.03 and 0.06 ppb [2–4]. These elements in the ocean primarily originate from terrigenous sources [5]. Atmospheric precipitation and river systems transport U and Th from land to the ocean, where they are eventually deposited in marine sediments [6,7].

Helium is a unique gas that is colorless, odorless, chemically inert, and has a low boiling point (4.22 K at standard temperature and pressure) [8]. It is a natural resource with strategic value and is widely used in high-tech industries and scientific research, such as aerospace, nuclear industries and cryogenics [9,10]. Pure helium gas reservoirs have not been discovered worldwide, as helium is typically found in association with natural gas [9]. As a result, the extraction of helium from natural gas reservoirs containing helium remains the primary method for industrial helium production [9–11]. However, owing to the increasing demand for helium (at an annual rate of 4–6%), the global reserves and production of helium are becoming increasingly limited [12,13]. The United States (40%), Qatar (19%), Algeria (16%), Russia (13%) and Canada (4%) collectively account for over 90% of global estimated helium resources, totaling approximately 51.9 billion cubic meters in 2017 [10,12–14]. Given current consumption rates, these reserves are projected to be depleted in about 230 years [15]. In addition, limited helium resources have been discovered in China, representing only 2% of global estimated helium resources (1.1 billion cubic meters) in the world [10]. However, China's annual consumption exceeds 25.7 million cubic meters, with over 80% dependent on imports [16]. This makes helium resource exploration in China essential, as the country is facing a shortage of helium.

Helium has two stable isotopes, ^3He and ^4He . ^3He mainly comes from mantle degassing ($^3\text{He}/^4\text{He} \approx 1\text{--}30 \text{ Ra}$, contrasting with crustal values of $<0.02 \text{ Ra}$, $\text{Ra} = \text{atmospheric } ^3\text{He}/^4\text{He} \text{ ratio of } 1.4 \times 10^{-6}$), whereas ^4He mainly comes from the decay of radioactive elements ^{238}U , ^{235}U , and ^{232}Th [17]. The main sources of helium in sedimentary basins are atmospheric helium, crustal helium (radioactive helium), and mantle-derived helium [8,18]. Atmospheric helium has little effect on helium concentration in gas reservoirs. The sources of helium in global gas fields that can be used for industrial production are mantle-derived helium and crustal helium [19]. Mantle-derived helium consists mainly of helium stored in the mantle during the early stages of Earth's formation [10]. Mantle-derived helium is characterized by an enrichment of ^3He ($^3\text{He}/^4\text{He} \geq 6 \text{ Ra}$) and can be transported into shallow crustal fluids via magmatism and faults, along with other gases, such as CO_2 , N_2 , and CH_4 [10,20]. Crustal helium (^4He) is usually found in natural systems in trace amounts, and helium concentrations higher than those in the air (5.24 ppm) are commonly discovered in groundwater and gas reservoirs [15].

The amount of helium produced in the crust directly depends on the age of the helium source rocks and the average U and Th contents in the rocks and minerals [8]. Thus, ancient U–Th-rich rocks are favored for helium formation. Marine black shales are rich in U and Th, and are generally recognized as major sources of crustal helium [15,18]. The average U contents in shale range from 4 to 60 ppm [21–23], and the average Th content in shale is 12 ppm [24,25]. For example, the Cambrian Niutitang Formation shale exhibit extreme U enrichment (up to 122 ppm) due to euxinic conditions, and the average Th content in the shales is approximately 10 ppm [26]. U and Th accumulation in shale is influenced mainly by organic matter (OM), redox conditions, terrigenous input, and minerals [21,27–29]. OM is capable of adsorbing and/or complexing U, but different types of OM have distinct U contents [21]. For example, algae-derived amorphous OM adsorbs up to 550 ppm U,

whereas terrestrial OM binds < 50 ppm U due to lower surface functional groups [21,28]. U–Th-bearing minerals, such as zircon, monazite and apatite, in shales contain significant U and Th contents (e.g., monazite: Th up to 300,000 ppm) [30]. The geochemical properties of U and Th differ during deposition, and Th is more stable than U. The stability and mobility of U are strongly influenced by its oxidation state [28]. Naturally occurring U is primarily composed of U (IV) and U (VI), with U (IV) being substantially less soluble than U (VI) [31]. U (VI) migrates more easily in oxidizing environments [32,33]. Other valence states of U (U (0), U (III), and U (V)) are almost unstable [28,34–36]. Th is usually insoluble in water, less active during low-temperature geological processes, and easily preserved in stable Th-bearing minerals. Th is transported mainly by terrigenous input and can be enriched in weathering residues [37]. Additionally, Th can migrate as organic complexes or colloids under suitable conditions [38,39].

The Upper Yangtze Platform contains abundant helium resources, and helium reservoirs have been found in the Weiyuan and Jinqu gas field, where the average helium concentrations are 0.2% and 0.07%, respectively [40,41]. However, the distribution of helium resources is complex, and the helium production capacity is quite different in this area [40,42]. The black shale of the Ediacaran Doushantuo Formation is widespread, indicating potential helium source rocks [43]. However, there are limited studies on the mechanism of U and Th accumulation in the Doushantuo Shales. In this work, shales and argillaceous dolomites from the Doushantuo Formation in the Upper Yangtze Platform are collected, and the argillaceous dolomites are used as comparative samples to investigate the mechanism of U and Th accumulation in marine sediments. This study aims to provide guidance for helium exploration and alleviate the shortage of helium resources.

2. Geological Setting

The Yangtze Platform runs from the western to eastern China, and the platform includes mainly Sichuan, Chongqing, Guizhou, Hubei, Anhui, and Jiangsu Provinces, with an area of approximately 500,000 km² (Figure 1A). The Yangtze Platform is one of the ancient platforms in China with abundant hydrocarbon resources [44]. The main exploration area of the Doushantuo Formation studied in this paper is located in the northeast and southeast of Chongqing, China (Figure 1B).

The Doushantuo Formation was deposited on top of the Nantuo Formation glacial deposits, with thicknesses ranging from 0 to 420 m (Figure 2A) [45]. The Doushantuo Formation is composed of four members, namely, Z₁d₁, Z₁d₂, Z₁d₃, and Z₁d₄, from the bottom to the top (Figure 2A) [43], and the formation consists mainly of grey argillaceous dolomite, micritic dolomite, and black shale (Figure 2A–C) [46]. The paleogeography of the Doushantuo Formation was influenced mainly by paleouplifts and marginal sags (Figure 1C–E) [43]. In the study area, the paleogeography exhibited by Z₁d₁ was dominantly shore and shallow-water shelf environments, and the paleogeography exhibited by Z₁d₂ was dominantly shallow-water shelf and deep-water shelf-basin environments (Figure 1C,D) [43]. Z₁d₃ exhibits dominantly mixed shelf and shallow-water shelf environments, with enhanced oxic conditions in the sedimentary environment. Z₁d₄ is absent or was not deposited in most parts of the Sichuan paleouplift, except for the marginal sags and shelves of western Hubei Province [43]. The Z₁d₁ cap dolomite was deposited mainly along the margin of the Sichuan Basin [45]. The primary lithology of Z₁d₂ is black shale, and the primary lithologies of Z₁d₃ are dolomite and argillaceous dolomite (Figure 2A–C). Z₁d₂ and Z₁d₃ formed during a transgressive–regressive cycle (Figures 1D,E and 2A) [43,46]. The primary lithology of Z₁d₄ is black shale (Figure 2A), which was formed during a transgressive–regressive cycle, along with the overlying massive carbonates of the Dengying Formation (Figure 2A) [45]. In the marginal sags, such as the Chengkou and Hefeng

sags, the average thicknesses of the source rocks are greater than 50 m (Figure 1F) [47], and the average total organic carbon (TOC) contents are generally greater than 2.0 wt.% [43]. On the other hand, in the Xiushan area, the average thicknesses of organic-rich shale range from 30 to 50 m (Figure 1F) [48], and the average TOC contents are usually greater than 1.0 wt.% [43].

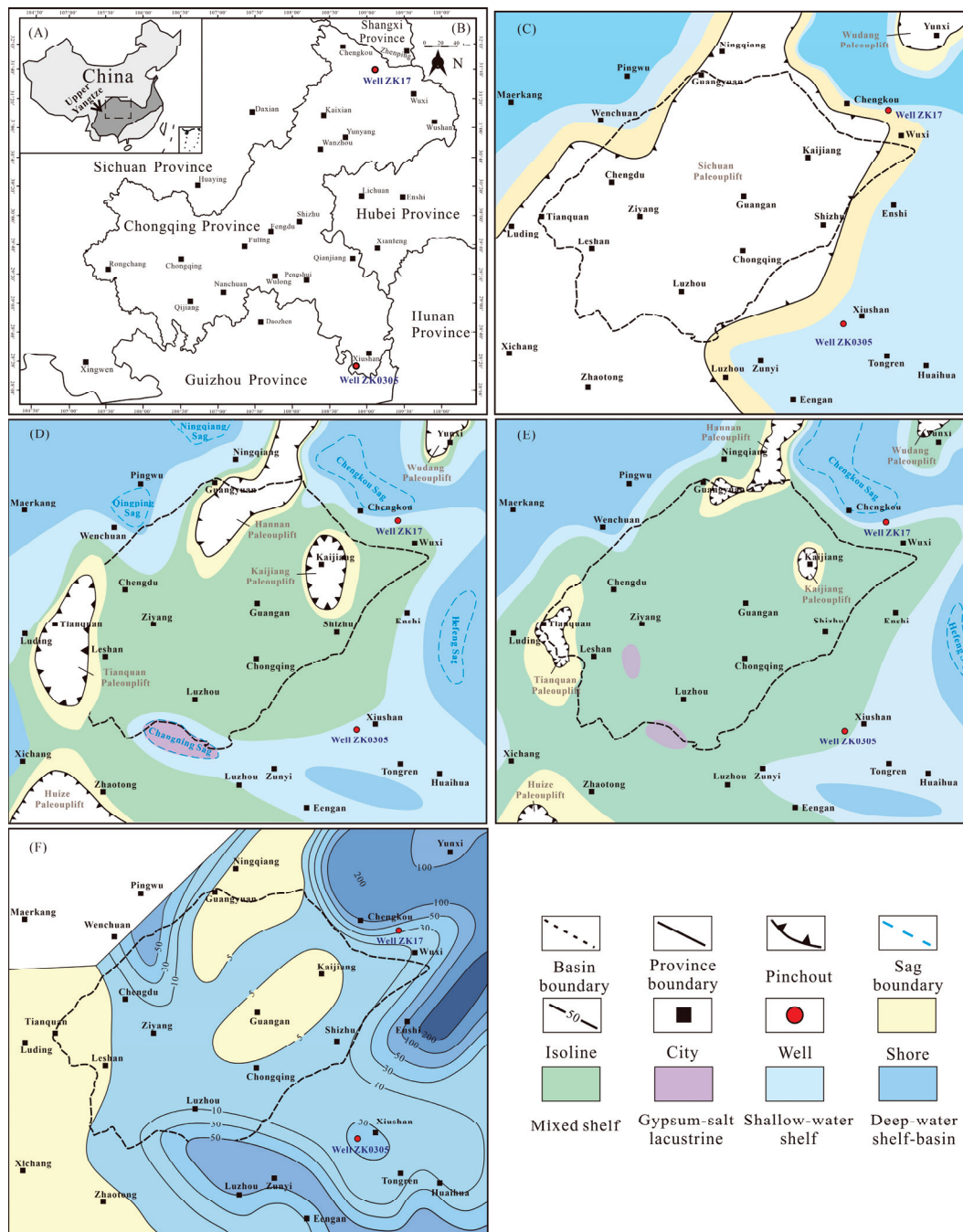


Figure 1. (A) Location of the study area in South China; (B) location map of Chongqing, showing sample sites. Modified from the work of Luo, et al. [49]. (C) Paleogeography of the Z₁d₁ in the Upper Yangtze Platform; (D) paleogeography of the Z₁d₂ in the Upper Yangtze Platform; (E) paleogeography of the Z₁d₃ in the Upper Yangtze Platform; (F) spatial variation in shale thickness of the Doushantuo Formation in the Upper Yangtze Platform. Figure (C–F) was modified from the work of Wang, Liu, Jiang, Huang, Wang, Xu, Jiang, Shi, Ren and Wang [43].

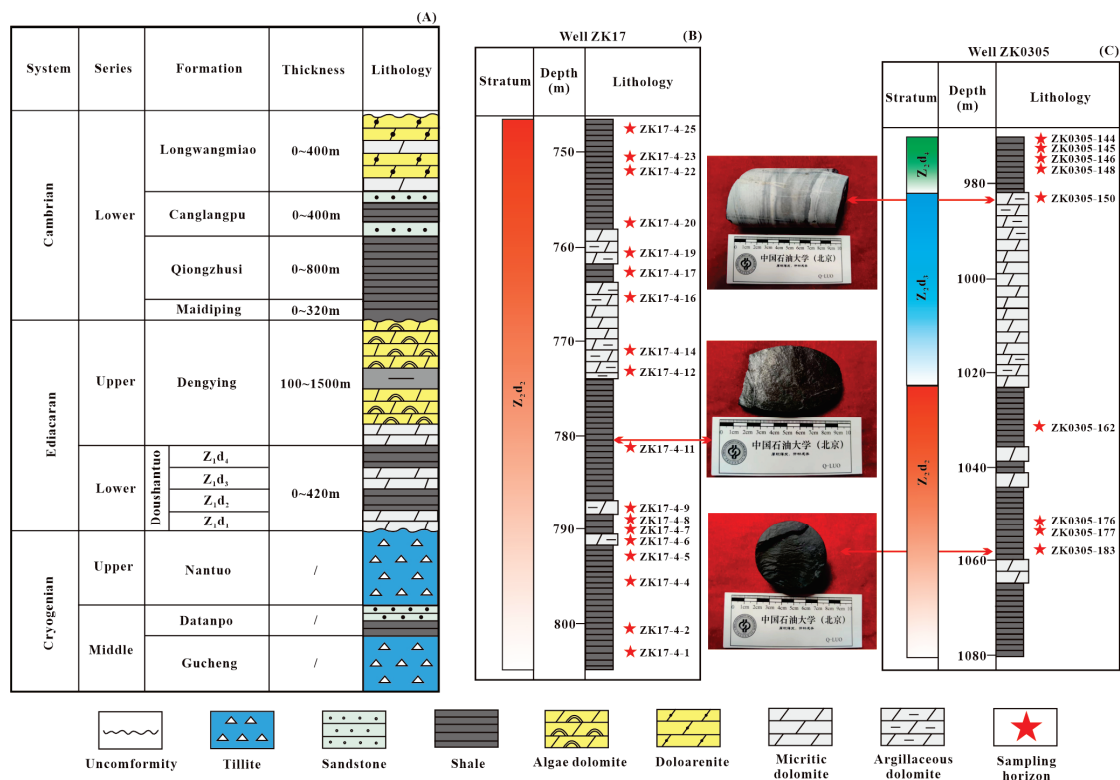


Figure 2. (A) Cryogenian–Cambrian stratigraphic column in the Upper Yangtze Platform (modified from Xiao, Cao, Luo, Tan, Xiao, He and Li [45]), as well as the stratigraphic columns of the Doushantuo Formation in the (B) well ZK17 and (C) well ZK0305. Note: “/” indicates “unknown”.

3. Sampling and Methods

3.1. Samples

A total of 27 Doushantuo Formation core samples were collected for this study; these samples included 13 black shales and 5 argillaceous dolomites from well ZK17 in Chengkou, Chongqing, and 8 black shales and 1 argillaceous dolomite from well ZK0305 in Xiushan, Chongqing (Figures 1B and 2B,C). The sampling intervals of the shales were generally of less than 7 m, while only a few argillaceous dolomites were collected for comparison purposes.

3.2. Organic Petrography

These fresh samples were ground to 200 mesh size. The powdered samples were processed with diluted HCl, and the residues were washed with distilled water more than 30 times and then dried. The TOC content was measured via a Leco CS-230 (Leco Corporation, St. Joseph, MI, USA). The core samples were cut into small blocks of 2 cm × 2 cm × 1 cm, which were subsequently cured with epoxy resin and dried. The smooth surfaces of the blocks were subsequently obtained by grounding and polishing via an EcoMet 250 machine (Buehler Ltd., Lake Bluff, IL, USA) with an AutoMet 250 (Buehler Ltd., Lake Bluff, IL, USA). Microscopic observations and in-source solid bitumen reflectance measurements were conducted on a Leica DM4500 (Leica Microsystems GmbH, Wetzlar, Germany) microscope equipped with a CRAIC photometer and a 50× oil immersion objective. Strontium titanate ($R_o = 5.36\%$), cubic zirconia ($R_o = 3.08\%$), and gadolinium–gallium–garnet ($R_o = 1.725\%$) were used as standard materials to calibrate the reflectance measurements. The experiments were performed at the National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum (Beijing).

3.3. Mineral Analysis

The mineralogical composition of the powdered samples was determined via X-ray diffraction (XRD), which was performed on a Bruker D2 Phaser (Billerica, MA, USA). The quantitative analysis of mineral components was performed via the Chinese standard procedure SY/T5163-2010 [50]. The rock samples were cut into small pieces and polished with sandpaper and argon ions. Then, they were coated with carbon for scanning electron microscope microscopy (SEM) analysis. The mineral distribution and composition were examined via a Zeiss Sigma 500 field emission SEM instrument (Oberkochen, Germany), equipped with an X-ray energy-dispersive spectrometry (EDS) instrument. XRD analyses were performed at the National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum (Beijing), and SEM analyses were performed at the National Research Center for Geoanalysis of the China Geological Survey.

3.4. Elemental Analysis

The concentrations of major and trace elements were analyzed at the Institute of Geochemistry, Chinese Academy of Sciences. A 50 mg powdered sample was blended with 1 mL of 38% HF and 2 mL of 68% HNO₃ in a polytetrafluoroethylene (PTFE) bomb. The container was then sealed and heated at 190 °C for 12 h. After cooling, 2 mL of HNO₃, 0.5 µg of Rh (as an internal standard), and 5 mL of deionized water were added, and the mixture was heated at 135 °C for 5 h. The sample was diluted with deionized water to a concentration of 1/3000th of the original concentration and tested via inductively coupled plasma–mass spectrometry (ICP–MS). Andesite, plagioclase gneiss, and slate were used as standards. The ICP–MS analysis achieved an accuracy better than ±5–10%. Sample preparation for major elements was similar to that for trace elements, with an internal standard of 1 mL of 10 ppm Cd (except for SiO₂). The treated solution was diluted 1000 times and tested via inductively coupled plasma–optical emission spectroscopy (ICP–OES). For SiO₂, 0.25 g of NaOH and 0.05 g of the powdered sample were added to a silver crucible and heated at 700 °C for 30 min. After cooling, deionized water was added, and the mixture was heated. After the products were dissolved, 5 mL of HCl was added, followed by the addition of deionized water to a solution volume of 250 mL. ICP–OES was also used to test the diluted solution. The loss on ignition (LOI) values were determined by calculating the mass difference before and after heating 1 g of the powdered sample at 900 °C for 1 h. The error of ICP–OES for the elements was less than ±5%.

3.5. Data Presentation

The enrichment factor (EF) is calculated by the following equation: $X_{EF} = (X/Al)_{\text{sample}} / (X/Al)_{\text{PAAS}}$ [51], in which, X is the target element and PAAS is Post-Archean Australian Shale [52].

The chemical index of alteration (CIA), chemical index of weathering (CIW) and plagioclase index of alteration (PIA) can serve as proxies for the reconstruction of the paleoclimate and weathering degree of the parent rock and are calculated as follows: $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, $CIW = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O)] \times 100$, and $PIA = [(Al_2O_3 - K_2O) / ((Al_2O_3 - K_2O) + CaO^* + Na_2O)] \times 100$ [53–55]. CaO* is the percentage of CaO in silicate minerals. The McLennan, et al. [56] correction method ($CaO' = CaO - 10/3 \times P_2O_5$), which assumes that silicate material has reasonable Ca/Na ratios, was used. CaO* equals the smaller of the values between those of CaO' and Na₂O. Generally, the CIA values range from 50 to 100, with different CIA values representing different climatic and weathering conditions: cold and arid climates and low chemical weathering (CIA = 50–60), warm and humid climates and intermediate chemical

weathering (CIA = 60–80), and hot and humid climates and extreme chemical weathering (CIA = 80–100) [53].

Trace elements (e.g., U) in marine shales are usually composed of terrigenous inputs (transported or particulate) and the authigenic fraction. It is often assumed that authigenic U can be approximately calculated by the difference between the bulk concentration and detrital fraction ($U_{\text{authigenic}} = U_{\text{bulk}} - U_{\text{bulk}} \times Al_{\text{bulk}} / Al_{\text{PAAS}}$) [52,57].

Eu anomalies can be utilized to determine the presence of hydrothermal influences in marine deposits [58]. Eu anomalies are calculated as follows: $\delta\text{Eu} = \text{Eu}_{\text{PAAS}} / (\text{Sm}_{\text{PAAS}} \times \text{Gd}_{\text{PAAS}})^{0.5}$, in which, X_{PAAS} represents the PAAS-normalized concentration of element X [52].

In order to quantitatively evaluate the helium generation of the Doushantuo Formation black shale on the Upper Yangtze Platform, a calculation formula for the amount of helium generation is established based on the formula proposed by Ballentine and Burnard [17]: $V_{\text{He}} = (1.207 \times 10^{-13} \times [\text{U}] + 2.868 \times 10^{-16} \times [\text{Th}]) \times \rho_s \times S_s \times h_s \times \text{yr}$, where V_{He} represents the volume of helium produced by the shale (m^3), $[\text{U}]$ denotes the concentration of U in the shale (ppm), $[\text{Th}]$ is the content of Th in the shale (ppm), yr denotes the age of the shale (years), ρ_s is the density of the shale (assumed to be 2.65 t/m^3), S_s is the distribution area of the shale (m^2), and h_s means the thickness of the shale (m).

4. Results

4.1. Organic Petrographic Characteristics

The primary maceral constituents of the shales are in-source solid bitumen, which appears grayish white when viewed under reflected light (Figure 3) [59,60]. Abundant in-source solid bitumen with heterogeneous distribution can be observed in the shales from the ZK17 well (Figure 3A,B). However, OM is more dispersed in the ZK0305 well sample (Figure 3F–I). Pyrite filled with OM can be observed in the shales (Figure 3C–E). The reflectance values of the in-source solid bitumen in ZK17 and ZK0305 obtained in the random direction are between 2.62% and 2.96% and between 3.01% and 4.52%, respectively. According to the formula developed by Luo, Zhang, Zhong, Wu, Goodarzi, Sanei, Skovsted, Suchý, Li, Ye, Cao, Liu, Min, Pan, Yao and Wu [59], the maturity values of the ZK17 are between 2.53% and 2.83%, and those of ZK0305 are between 2.86% and 4.29%, indicating that the OM in the Doushantuo Formation is in the overmature stage.

4.2. Geochemistry

4.2.1. TOC

The shales displayed a wide variation in TOC values, ranging from 0.06 to 34.58 wt.% (Table S1), with an average of 6.47 wt.%. The shales from well ZK17 have a higher average TOC content of 6.85 wt.% than those from well ZK0305 (Table S1). The ZK17-4-1 sample has the highest TOC content of 34.6 wt.% and is a sample of an abundant in-source solid bitumen, as shown in Figure 3A,B. The TOC contents of samples ZK0305-162 and ZK0305-176 are notably lower than those of the other shales, at 0.06 wt.% and 0.08 wt.%, respectively (Table S1). The argillaceous dolomites have an average TOC content of 0.98 wt.%, with a range of 0.05 to 2.87 wt.% (Table S1). The variable range of TOC in the shales and dolomites indicates the heterogeneity of the OM distribution in the Doushantuo Formation.

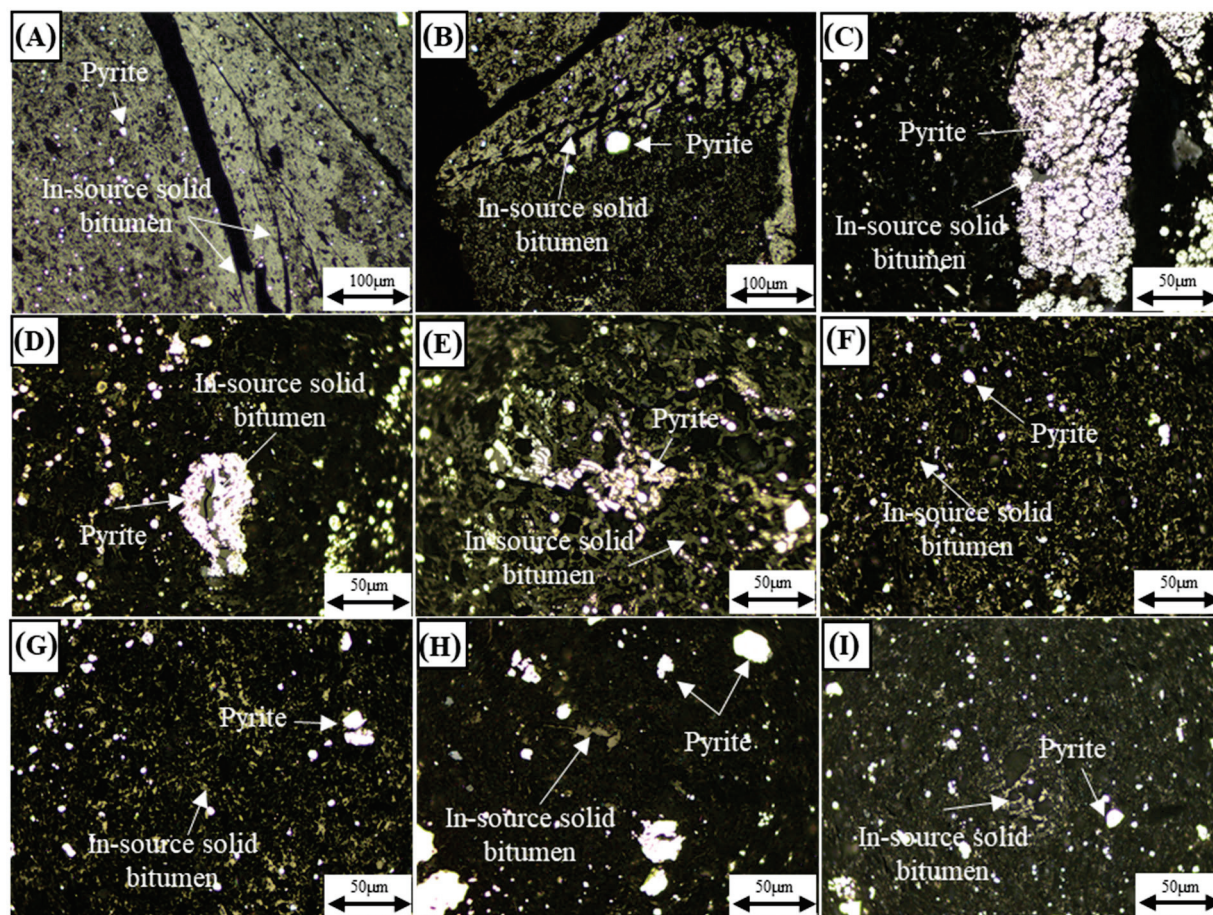


Figure 3. Photomicrographs of in-source solid bitumen and pyrite in reflected white light and oil immersion. (A,B) from ZK17-4-1, TOC is 34.58 wt.%; (C,D) from ZK17-4-3; TOC is 9.48 wt.%; (E) from ZK17-4-4; (F) from ZK0305-144; (G) from 0305-145; (H,I) from ZK0305-146, TOC is 6.18 wt.%; (C–E) have the phenomenon that pyrite filling OM.

4.2.2. Major Elements

The average concentrations of major elements in the shales are 56.7 wt.% for SiO_2 , 11.6 wt.% for Al_2O_3 , 5.5 wt.% for Fe_2O_3 , 2.5 wt.% for MgO , 4.0 wt.% for CaO , 1.2 wt.% for Na_2O , 3.4 wt.% for K_2O , 0.2 wt.% for MnO , 0.7 wt.% for TiO_2 , and 1.3 wt.% for P_2O_5 (Table S1). The samples have higher average concentrations of MgO , CaO , Na_2O , MnO , and P_2O_5 and lower concentrations of SiO_2 , Al_2O_3 , Fe_2O_3 , K_2O , and TiO_2 than those of the post-Archean Australian shale (PAAS; Figure 4A) [52]. The argillaceous dolomites contain 32.2 wt.% SiO_2 , 3.1 wt.% Al_2O_3 , 1.8 wt.% Fe_2O_3 , 7.7 wt.% MgO , 15.5 wt.% CaO , 0.3 wt.% Na_2O , 1.0 wt.% K_2O , 10.3 wt.% MnO , 0.2 wt.% TiO_2 , and 0.3 wt.% P_2O_5 . These dolomites have higher average concentrations of MgO , CaO , and MnO and lower concentrations of the other elements than post-Archean Australian shale (PAAS) (Figure 4B) [52].

4.2.3. Trace Elements

The shales contain an average of 17.58 ppm U and 9.78 ppm Th, and the argillaceous dolomites have averages of 3.52 ppm U and 2.75 ppm Th, which are much lower than those in the shales (Table S1). All trace elements obtained were normalized to PAAS (Figure 5) [52]. On average, the shales and argillaceous dolomites are enriched in U and depleted in Th compared with PAAS (Figure 5A,B).

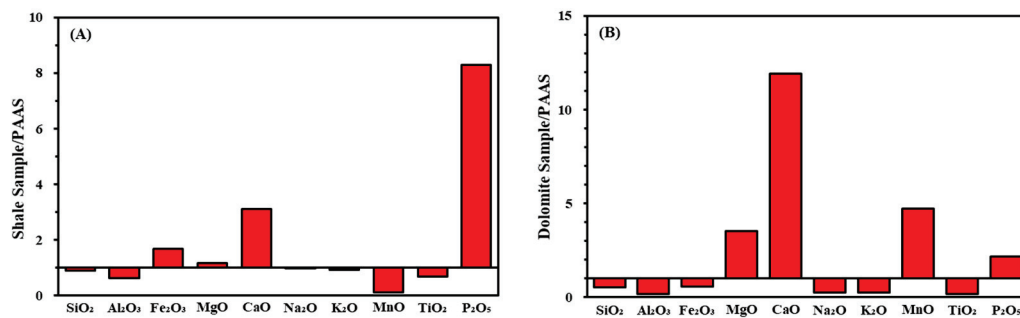


Figure 4. PAAS-normalized [52] Taylor and McLennan, 1985; (A) major element diagrams for the Doushantuo Shales; (B) major element diagrams for the Doushantuo argillaceous dolomites.

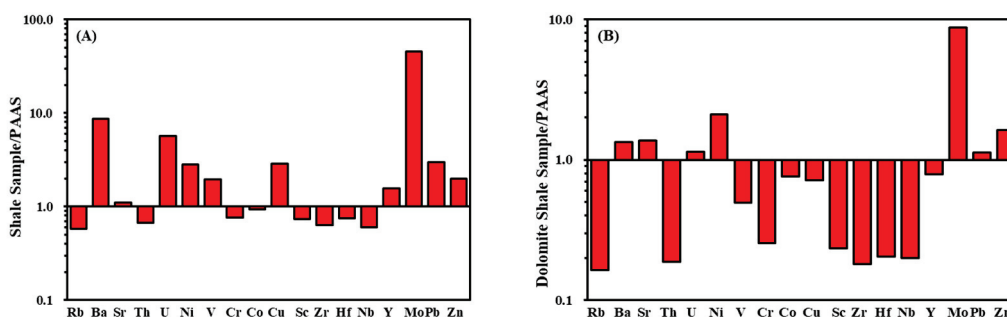


Figure 5. PAAS-normalized [52]; (A) trace element diagrams for the shales; (B) trace element diagrams for the argillaceous dolomites.

For the redox-sensitive trace elements, the average Mo, V, Pb, Zn, Cu, and Ni contents in the shales are greater than those in PAAS (Figure 5A). Th correlates poorly with redox-sensitive trace elements, and U has moderate positive correlations with V, Cr, Zn, Cu, Ni, and Pb in shales (Table S2; $r = 0.67, 0.81, 0.71, 0.72, 0.55$, and 0.54 , respectively). The average Mo, Pb, and Zn contents in the argillaceous dolomite are relatively high compared with those in PAAS, and the average contents of V, Ni, and Cu are lower than those in PAAS. The U and Th contents in the argillaceous dolomite do not show any correlation with other mostly redox-sensitive elements (Table S3).

4.2.4. Minerals in the Shale

The shales mainly comprise quartz, clay minerals, dolomite, and iron–dolomite, and the argillaceous dolomites mainly comprise dolomite and ankerite, along with some manganite, siderite, pyrite, hematite, calcite, feldspar, and clay minerals (Table S1, Figures 6 and 7). Quartz is the most common mineral in shale, with an average content of 29.9 wt.% (Table S1). The quartz content of argillaceous dolomites (mean of 11.5 wt.%) is lower than that of shales (mean of 29.9 wt.%; Table S1). Quartz appears grayish-white under the SEM, and it is predominantly irregular with angular, semi-angular, or subrounded shapes, with crystal sizes ranging from micrometers to nanometers (Figure 7B–D,F). Clay minerals are another common mineral in shale, with an average content of 32.9 wt.%. However, the argillaceous dolomites contain lower clay mineral contents than shales, averaging 10.1 wt.%. Under SEM, micron-sized elongated illite can be observed (Figure 7A). The average percentages of dolomite and ankerite in the shales are 10.9 wt.% and 1.6 wt.%, respectively. In the argillaceous dolomite, the average percentages of dolomite and ankerite are 27.4 wt.% and 26.1 wt.%, respectively, which are much greater than those in the shales (Table S1 and Figure 6). Fe^{2+} can replace Mg^{2+} in the dolomite lattice to form ankerite. As an isomorphic phase of dolomite, ankerite has similar optical properties and crystal structures [61]. Both dolomite and ankerite appear grayish white in color under SEM (Figure 7G,H). The average pyrite content in the shales is 6.4 wt.%, and the average pyrite

content in argillaceous dolomites is 5.1 wt.% (Table S1 and Figure 6). The pyrite in the sample is mainly euhedral pyrite and framboidal pyrite (Figures 3 and 7C,D). Rhodochrosite is present in four argillaceous dolomites, with an average content of 19.1 wt.% (Table S1 and Figure 6). The barite content is low, at less than 1 wt.%. Sphalerite is not detectable in the XRD analysis but is observable via SEM (Figure 7F). Because of the presence of heavy elements, the secondary and backscattered electron images of sphalerite and barite are very bright (Figure 7E,F). Small quantities of these minerals are observable only via SEM (Figure 7A,C) within the shales. A higher apatite content is observable in sample ZK4-16, with a content of 13.5 wt.% (Table S1 and Figure 6). SEM–EDS reveals that the dominant form of apatite in the shale is chlorapatite, which has an irregular shape (Figure 7C). Zircons are dispersed mainly in granular form with small particle sizes (less than 5 μm) and appear grayish-white (Figure 7A).

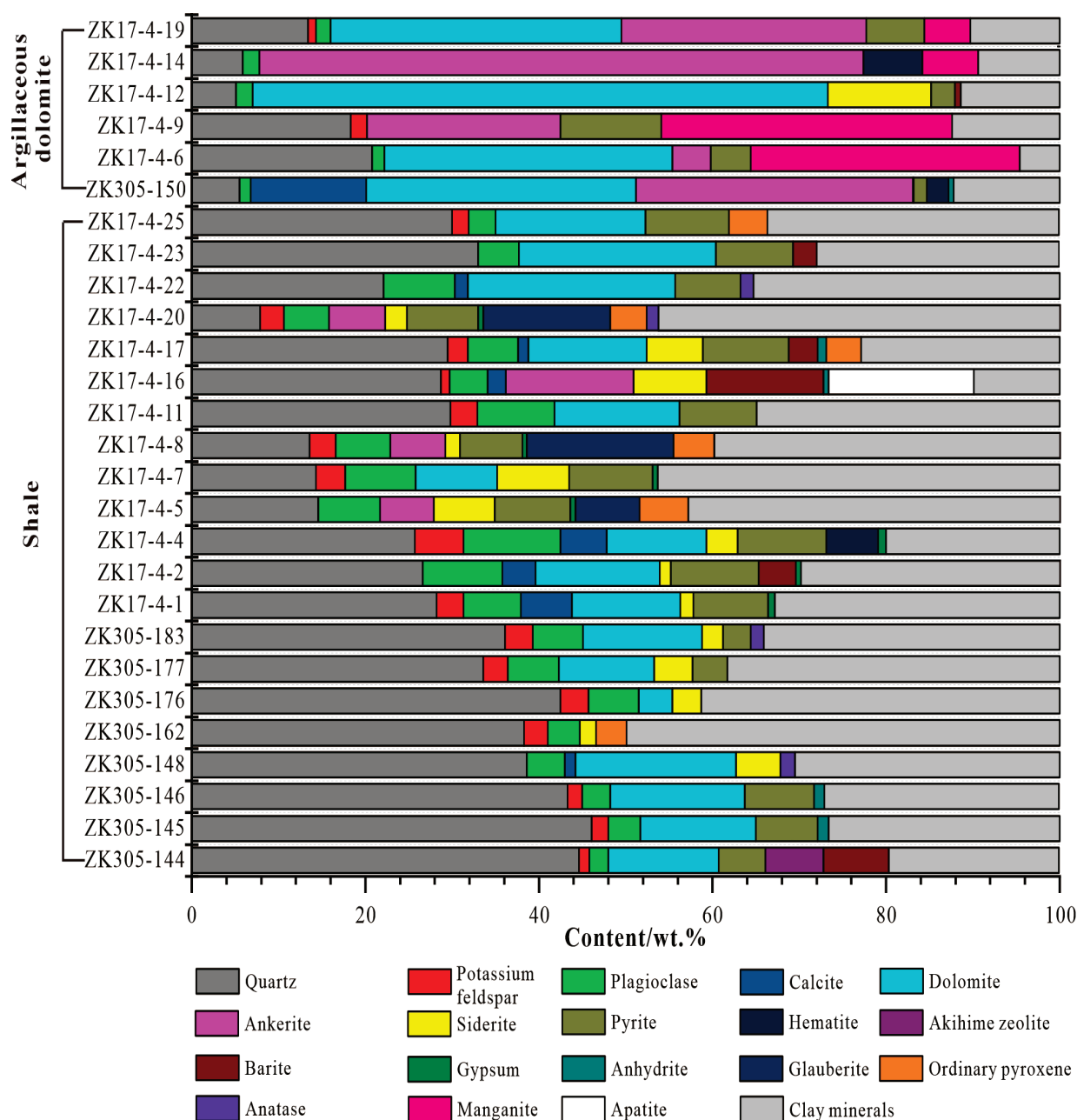


Figure 6. The mineral composition of shales and argillaceous dolomites.

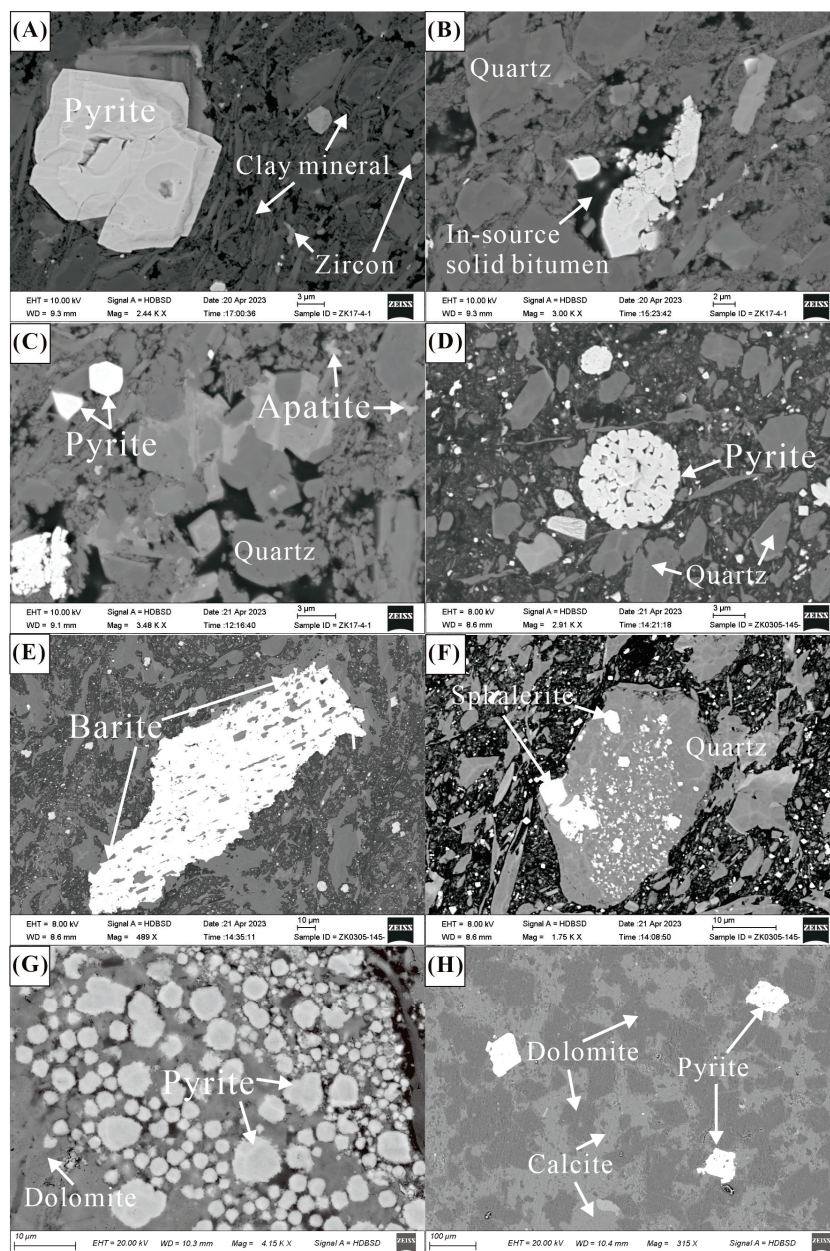


Figure 7. SEM images of minerals in shales and argillaceous dolomites in the Doushantuo Formation. (A–C) from ZK17-4-1; (D–F) from ZK0305-145; (G) from ZK17-4-9; (H) from ZK0305-150.

5. Discussion

5.1. Sedimentation Conditions and Environments

(1) Terrigenous input

In previous studies, Al, Ti, Zr and Th were commonly used to indicate terrigenous input [62]. Al and Ti are found primarily in heavy minerals and aluminosilicates, such as rutile and ilmenite [27], and remain relatively constant during diagenesis [51]. The Al_2O_3 content of the shales ranges from 2.56 to 17.7 wt.%, with an average of 11.55 wt.%, and the Ti content ranges from 636.6 to 6019.6 ppm, with an average of 4010.5 ppm (Table S1). The argillaceous dolomite has lower Al_2O_3 and Ti contents of 1.83–6.67 wt.% and 576.9–2256.0 ppm, averaging 3.11 wt.% and 1081.8 ppm, respectively (Table S1). The Al_2O_3 and Ti contents show comparable trends throughout the stratigraphic column (Figure 8A,B).

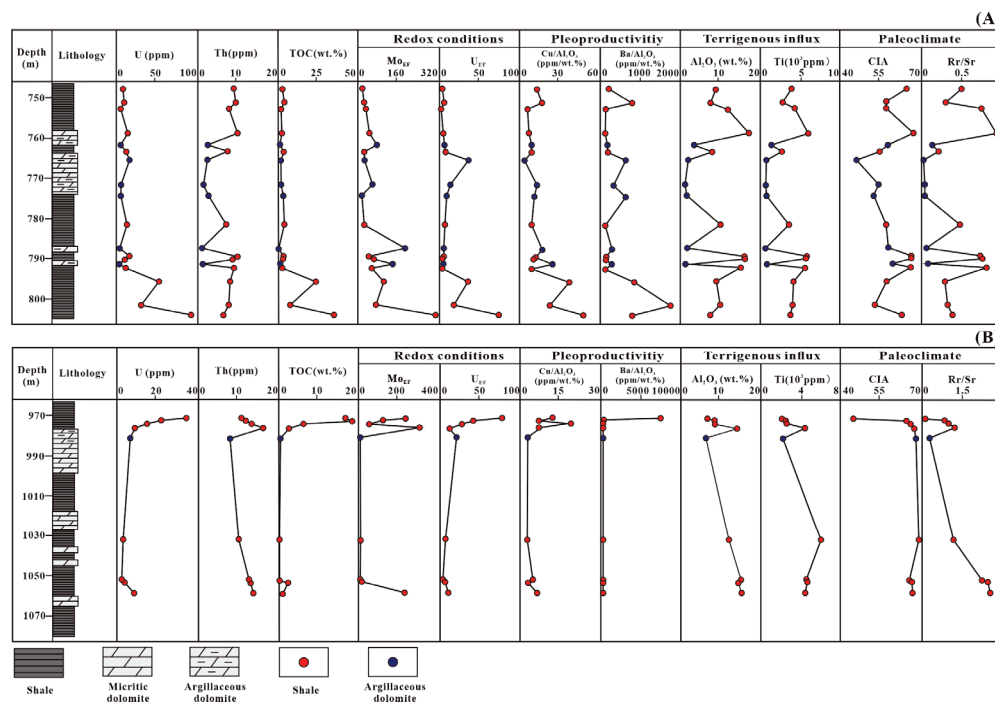


Figure 8. Stratigraphic distributions of U contents, Th contents, TOC contents, terrigenous influx, redox, paleoproductivity and paleoclimate proxies of (A) well ZK17 and (B) well ZK0305 for the Doushantuo Formation in the Upper Yangtze Platform.

(2) Redox conditions

Redox-sensitive elements, such as Mo, U, V, and Ni, and their ratios, such as Ni/Co and U/Th, can serve as paleoredox proxies [63]. As shown in Table S1, Ni/Co and U/Th in the shales are in the ranges of 1.95–35.85 (mean of 7.42) and 0.22–14.47 (mean of 2.32), respectively, and they are 2.77–8.60 (mean of 6.18) and 0.82–2.91 (mean of 1.63) in argillaceous dolomites, respectively, indicating oxic–dysoxic–anoxic depositional environments for the shales and argillaceous dolomites (Table S1 and Figure 9A) [64,65]. The enrichment of Mo and U in marine sediments is mainly controlled by the average concentrations of Mo and U in the water column, the redox state of the water column, and the hydrological characteristics of the basin [51]. U is activated in the Fe (III)–Fe (II) reduction zone and can be transferred to sediments under reducing conditions [66], whereas Mo is enriched in sediments only when seawater contains H₂S [67]. Therefore, the Mo–U covariation pattern is a practical alternative for extrapolating the redox conditions of shales [29,68]. The Mo_{EF} values of the shales range from 0.96 to 288.51, with an average of 76.45, and the U_{EF} contents range from 1.16 to 69.7, with an average of 11.44 (Table S1 and Figure 9B), indicating that anoxic–euxinic conditions characterize the redox conditions of the shales.

(3) Paleoproductivity

Cu is usually present in oxidized water as organometallic complexes, with limited Cu (II) ions [27,69]. During decomposition of the organic matter at the bottom of the seawater column, Cu is released into the pore water and adsorbed by the pyrite under anoxic conditions [70,71]; so, it can be used as an effective proxy to evaluate paleoproductivity. Ba is also widely used in paleoproductivity assessments [72,73]. Al₂O₃ is commonly used to remove the effects of terrigenous input [74]. In this study, Cu/Al₂O₃ and Ba/Al₂O₃ were employed as proxies for paleoproductivity. As shown in Table S1, the Cu/Al₂O₃ ratios of the shales range from 2.37 to 45.98 ppm/wt.%, with an average of 13.71 ppm/wt.%, and the Ba/Al₂O₃ ratios range from 94.99 to 7421.65 ppm/wt.%, with an average of 669.81 ppm/wt.%. The argillaceous dolomite has a lower Cu/Al₂O₃ and Ba/Al₂O₃ ratios of 2.68–26.05 ppm/wt.% and 172.37–563.79 ppm/wt.%, averaging 14.97 ppm/wt.% and 301.83 ppm/wt.%, respec-

tively (Table S1 and Figure 8), indicating that the paleoproductivity of the shales is greater than that of the argillaceous dolomites [51].

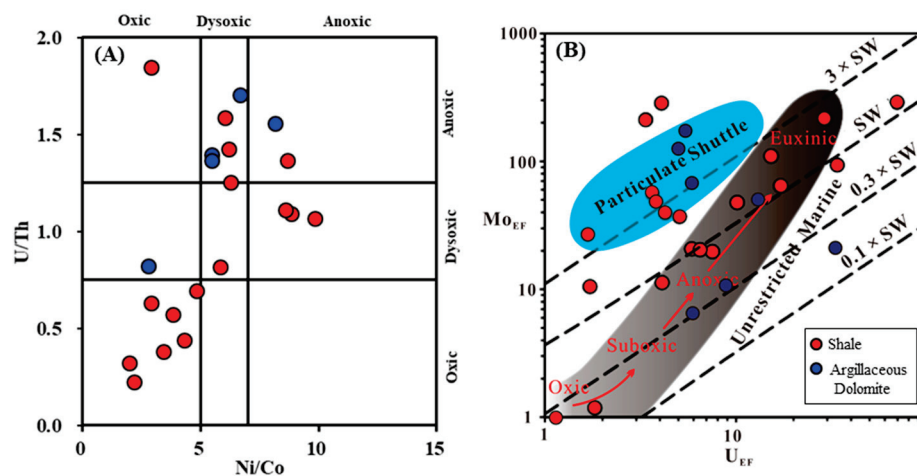


Figure 9. Covariation in (A) U/Th versus Ni/Co and (B) Mo_{EF} versus U_{EF} for the shales and argillaceous dolomites in the Upper Yangtze Platform (modified from Algeo and Tribouillard [29]).

(4) Paleoclimate and paleoweathering

The Doushantuo Formation has moderate CIA values, ranging from 44.90 to 68.91, with a mean of 60.57 (Table S1), suggesting a semi-humid climate and intermediate chemical weathering. The calculated CIW and PIA values for the Doushantuo Formation range from 51.94 to 89.18 (mean of 75.54) and 43.01–84.24 (mean of 68.44), respectively, indicating a semi-humid climate and intermediate chemical weathering during its deposition. The Rb/Sr ratio is often used to reconstruct the paleoclimatic evolution [64]. The Rb/Sr values of the Doushantuo Formation range from 0.02 to 2.60, with an average of 0.70, indicating a semi-humid climate [75].

5.2. Source of Uranium and Thorium

La/Sc and Th/Co ratios can be employed in provenance analysis as silicic rocks are enriched in La and Th and depleted in Sc and Co compared with basic rocks [50,76]. As shown in Figure 10a, the shales are derived from silicic rocks. On the basis of Hayashi, et al. [77] and Figure 10b, the samples suggest derivation from a felsic source. Wang, et al. [78] reported that Neoproterozoic sedimentary rocks are sourced mainly from Neoproterozoic magmatic rocks, which are widely distributed in the northern part of the Yangtze Platform [78,79]. Hu [80] suggested that sediments in Z₁d₁, Z₁d₂ and Z₁d₃ were derived from Neoproterozoic magmatic rocks in the northern part of the Yangtze Platform, and that sediments in Z₁d₄ were derived from the Kongling Group in the northern part of the Yangtze Platform. The Kongling Group is mainly composed of Paleoproterozoic granitic gneiss and metasedimentary rocks [81]. The CIA, CIW, PIA and Rb/Sr values indicate a semi-humid climate and intermediate chemical weathering in the provenance area (Table S1). Therefore, the parent rocks distributed in the northern part of the Yangtze platform (i.e., Neoproterozoic magmatic rocks and/or the Kongling Group) could have provided U and Th after weathering during the deposition of the Doushantuo Formation. Atmospheric precipitation can transport the weathering products of parent rocks to surficial river systems, after which the river delivers soluble U (VI) and insoluble Th-containing minerals to the ocean [5,82]. U is deposited under increasing reducing conditions and forms authigenic U in the water column and/or pore water, which accounts for 40 to 70% of the total flux of riverine U input [6,7]. Th in shales is derived mainly from terrigenous

input; however, the extremely low deposition rate of the Doushantuo Formation (≤ 5.6 m/Myr) was not conducive to Th accumulation because of its geochemical inertness [45].

The $U_{\text{authigenic}}$ values in the shales range from 0.52 to 52.67 ppm, with an average of 8.44 ppm, and the $U_{\text{authigenic}}$ values in the argillaceous dolomites range from 1.40 to 4.27 ppm, with an average of 2.80 ppm (Table S1). Authigenic U values range from 8% to 86% of the total U in shales, with an average of 39%, and range from 64% to 90% of the total U in argillaceous dolomites, with an average of 84% (Table S1). Zheng, et al. [83] reported that accumulation rates of authigenic U range from 20 to 70 $\mu\text{g}/\text{cm}^2$ kyr in marine sediments and that a substantial amount (one-third to two-thirds) of the authigenic U is eventually preserved in marine sediments. Therefore, authigenic U is an important source of U in the Doushantuo Formation. Owing to its geochemical inertness and insolubility, authigenic Th is usually absent in marine sediments.

Hydrothermal fluids can supply trace elements (e.g., U and Th) to lakes or the ocean [84,85]. Eu anomalies can be utilized to determine the presence of hydrothermal influences in marine deposits [58]. The δEu values of the shales range from 0.98 to 3.38, with an average of 1.20 (>1), and the δEu values of the argillaceous dolomites range from 1.12 to 1.22, with an average of 1.16 (>1 , Table S1), indicating that hydrothermal input was common during the deposition of the Doushantuo Formation, which is consistent with the findings of Liu, et al. [86] and Xiao, Cao, Luo, Tan, Xiao, He and Li [45].

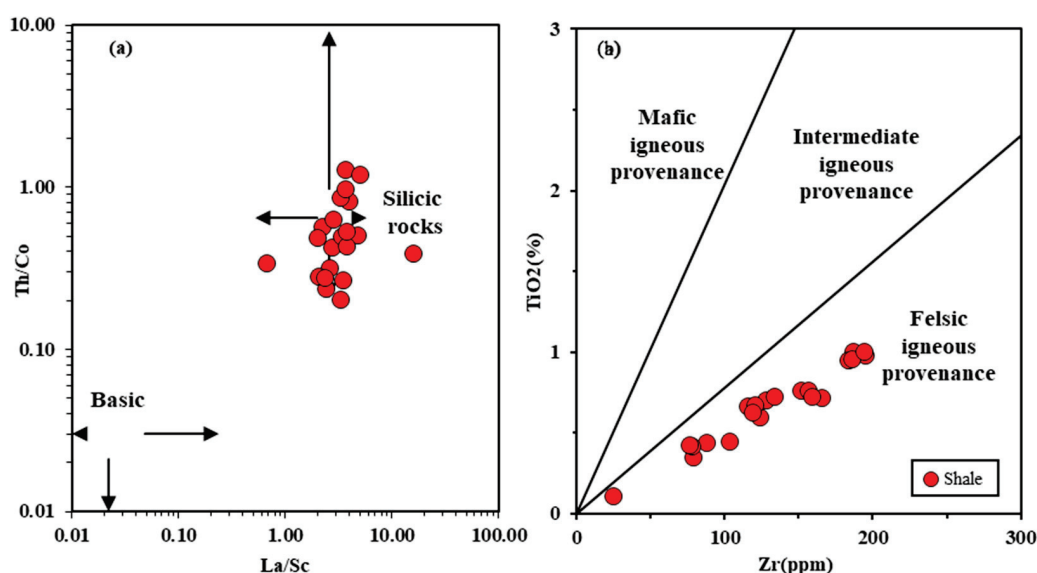


Figure 10. (a) Th/Co-La/Sc [87]; note that shales plot close to the silicic rock; (b) TiO_2 -Zr [77]; note that shales plot falls into the felsic igneous provenance.

5.3. Factors Controlling Uranium Accumulation

5.3.1. Uranium and Redox Conditions

Under oxic–suboxic circumstances, uranyl carbonate complexes ($\text{UO}_2(\text{CO}_3)_3^{4-}$), which are chemically inert, are the major form of soluble U (VI) present in the oxidized sedimentary environment [7,66]. U is reduced to U (IV) under reducing conditions and is commonly in the form of insoluble authigenic U (UO_2) [35]. Particularly, under euxinic condition, U is more easily separated from the water [51]. U is positively correlated with Ni/Co and U/Th in the shales ($r = 0.85$ and 0.91 , respectively; Figure 11A,B), demonstrating that U accumulation is controlled by redox conditions and that the reducing environment is beneficial for U accumulation.

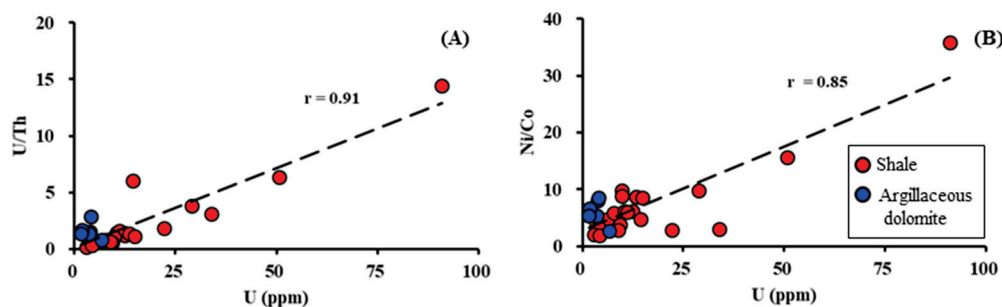


Figure 11. Cross-plots of U content versus (A) U/Th and (B) Ni/Co.

5.3.2. Uranium and Organic Matter

There are three primary forms of U in the crust: (1) independent minerals, such as uraninite and pitchblende [28]; (2) isomorphous minerals, in which U is replaced by other elements (e.g., Ca^{2+} and Zr^{4+}), forming U-bearing minerals, such as apatite [88]; and (3) dispersed adsorption state, which is a prevalent form in which U is mainly adsorbed/complexed on the surfaces of minerals and OM in rocks [89]. Independent U-bearing minerals were not found in the shales, and few isomorphous U-bearing minerals (zircon and apatite) were found (Table S1 and Figure 7). Notably, a strong positive correlation exists between the U and TOC contents in the Doushantuo Formation ($r = 0.95$, Figure 12A), and shale sample ZK17-4-1 has the highest TOC and U contents (Table S1). Many studies have also reported positive correlations between U and OM, such as $r = 0.86$ indicating the positive correlation in the U deposit located north of the Aquitaine Basin [90] and $r = 0.92$ indicating the positive correlation in the natural soil in the Dischma Valley [91]. OM contains aliphatic, aromatic, carboxyl, hydroxyl, phenolic, and thiosulfate functional groups that determine the solubility and bonding capabilities of OM [28]. Under reducing conditions, OM can be better preserved, and the hydroxyl or carboxyl groups in OM can adsorb (or complex) U in the water column and/or pore water to form uranyl–organometallic complexes [29,91]. Gad, et al. [92] reported that biosorption experiments of U were carried out using five kinds of local algae in Egypt, and the results revealed that the algae had a strong adsorption capacity for U. There was a poor correlation between the U and TOC contents in argillaceous dolomites ($r = 0.13$, Figure 12B), indicating that U may exist mainly in the inorganic phase. Authigenic U (UO_2) is the predominant form of U in argillaceous dolomite and typically coats the surfaces of clastic grains [82]. $\text{Ba}/\text{Al}_2\text{O}_3$ and $\text{Cu}/\text{Al}_2\text{O}_3$ are positively correlated with the U content (Figure 12C,D), suggesting that higher paleo-productivity is favorable for U accumulation in sediments. Liu, Mastalerz, Schieber and Teng [21] reported that U in the New Albany Shale is mainly associated with amorphous OM (average U content of ~ 550 ppm). The source of OM was dominantly lower aquatic organisms, such as algae, during the deposition of the Doushantuo Formation. However, the macerals were dominantly in-source solid bitumen in the Doushantuo Formation because of the overmature thermal maturity (Figure 3). Some U can be expelled from source rocks at percentages ranging from 43 to 48% during the process of hydrocarbon generation, as indicated by laboratory simulation experiments [93]. Thus, the oil retained in the shale also contains significant U, and the retained oil is transferred to in-source solid bitumen via thermal cracking [59], resulting in U enrichment in the in-source solid bitumen. This can also be confirmed by the fact that abundant in-source solid bitumen and a high U content are simultaneously present in shales ZK17-4-1, ZK17-4-3, and ZK17-4-4 (Figure 3A–I). The symbiosis of U and solid bitumen has also been found in carbonate-hosted U deposits in Guizhou, China, and U is thought to be derived mainly from the expelled oil [94].

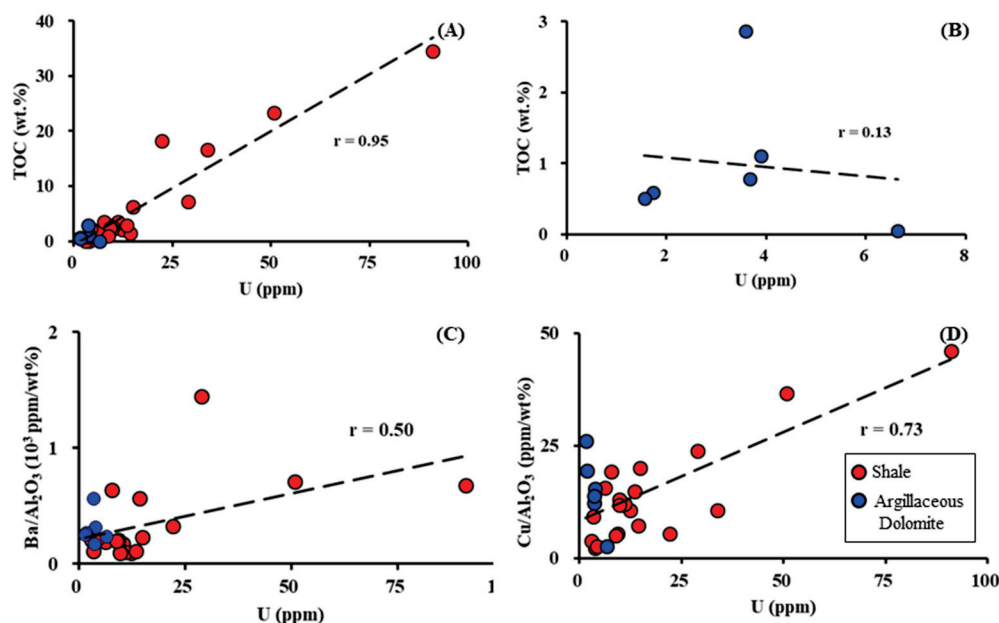


Figure 12. Cross-plots of (A) U versus TOC; (B) magnification of argillaceous dolomites in (A); (C) U versus Ba/Al₂O₃; and (D) U versus Cu/Al₂O₃.

5.4. Factors Controlling Thorium Accumulation

There is no apparent correlation between the Th and TOC contents in these samples (Figure 13A), suggesting that Th exists mainly in the inorganic phase rather than in OM. Th usually exists in the tetravalent form as ThO₂ and ThSiO₄ or in some accessory minerals (e.g., monazite and zircon) and can also be adsorbed by some minerals (e.g., hematite and clay minerals) [95,96]. Some Th-containing minerals, such as apatite and zircon, which are sourced from the terrigenous and hydrothermal inputs, can be found in shales (Figure 7A,C). The ability of clay minerals to adsorb Th (IV) has been studied under laboratory conditions [97–99]. For example, as the pH of a solution increases from 1 to 4.5, the affinity of Th to kaolinite becomes significantly greater, resulting in the formation of inorganic–cationic complexes [100]. However, Th is usually adsorbed by clay minerals in the form of small Th-containing minerals in marine sediments [101]. The clay mineral contents in the shales range from 9.9 wt.% to 49.9 wt.%, with an average value of 32.9 wt.%, and the clay mineral contents of the argillaceous dolomites range from 4.6 wt.% to 12.4 wt.%, with an average value of 10.1 wt.% (Table S1). The Th content tends to increase with increasing clay mineral content in the studied samples (Figure 13B), implying that Th is mainly distributed in the clay mineral matrix.

There are positive correlations between Th and Rb, Cs, Al₂O₃, SiO₂, and KO₂ in the collected samples (Figure 13C–G). Zhao, et al. [102] reported that Rb and Cs in Jurassic No. 6 coals from the Iqe Coalfield in the Qaidam Basin, China, were adsorbed mainly by K-rich clay minerals and that the sediment was also enriched in Th. Ward, et al. [103] reported a robust Rb–K correlation in Permian coals. Rb is bound more strongly to the inorganic phase in sediments, and clay minerals have a stronger capacity for adsorbing Rb than that of OM [104]. In sediments, OM and clay minerals can adsorb Cs [102]. However, Cs is more commonly found in K-rich minerals, such as illite and montmorillonite, as it can isomerize potassium [105]. Therefore, Th, Rb, and Cs in the Doushantuo Formation may be adsorbed by K-rich clay minerals (Table S4).

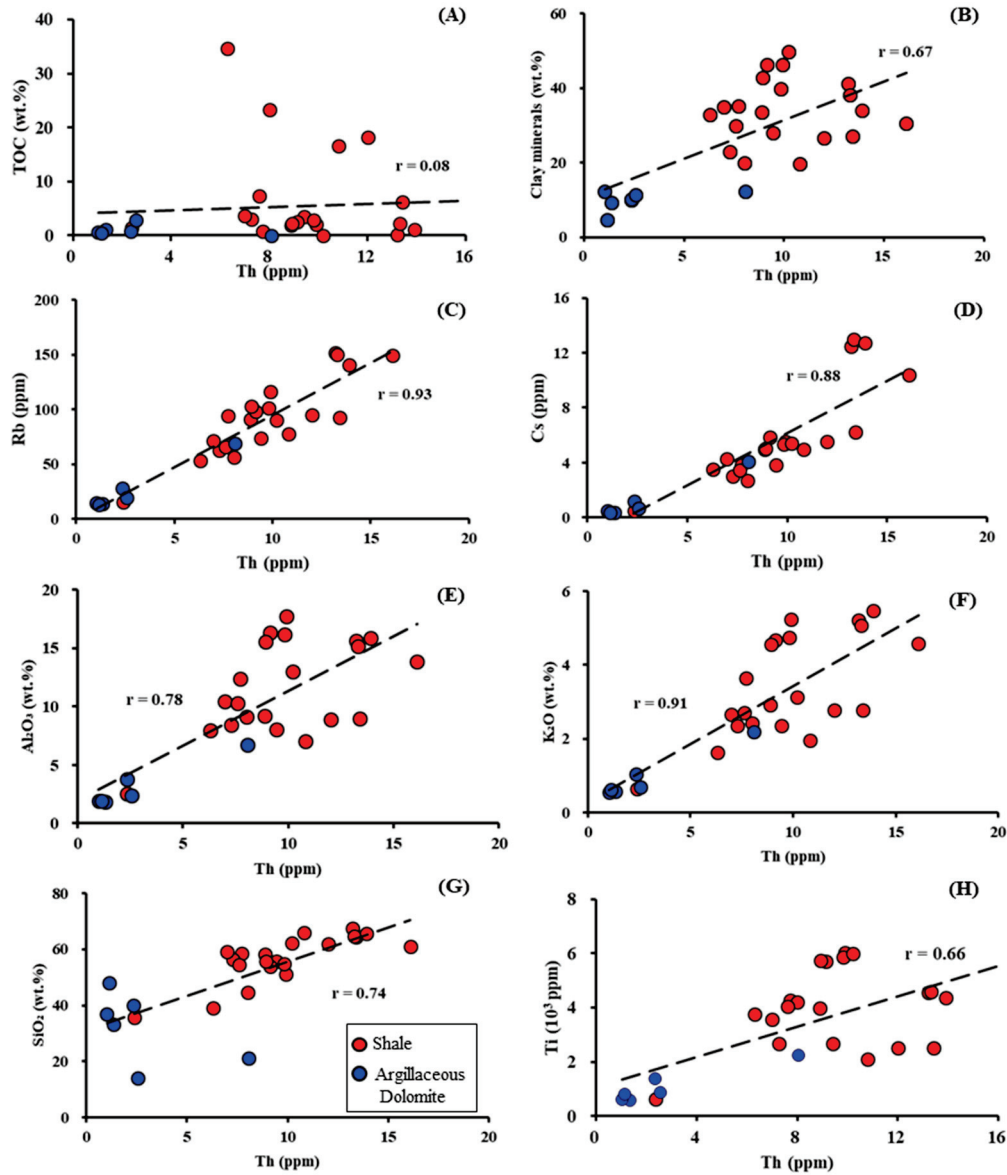


Figure 13. Cross-plots of Th content versus (A) TOC, (B) clay minerals, (C) Rb, (D) Cs, (E) Al_2O_3 , (F) K_2O , (G) SiO_2 , and (H) Ti content.

The positive correlations between Th and Al_2O_3 and Ti contents indicate that Th is derived mainly from terrigenous input (Figure 13E,H). An adequate supply of Th is necessary for Th accumulation in marine sediments. As mentioned earlier, Th is separated from the parent rocks (e.g., Neoproterozoic magmatic rocks and/or the Kongling Group) after weathering and transported by surficial river systems along with the terrigenous input. The average Al_2O_3 and Ti contents in well ZK17 are 8.67 wt.% and 3190 ppm, respectively, which are lower than those in well ZK0305 (11.68 wt.% Al and 3700 ppm Ti), indicating that Xiushan has more considerable terrigenous input than Chengkou. The water depth in Xiushan was shallower than in Chengkou during the sedimentation of the Doushantuo Formation because of transgression and regression of the sea [43]. Thus, Xiushan was more influenced by terrigenous input, resulting in a higher Th content in Xiushan (Table S1). However, there is a notable connection between the Th and Al_2O_3 and Ti contents in samples from Chengkou (Figure 14A,B), and weak-to-moderate correlations were observed between the Th and Al_2O_3 and Ti contents in samples from Xiushan (Figure 14C,D). These

distinct correlations suggest that excessive terrigenous input may dilute Th concentrations in the formation.

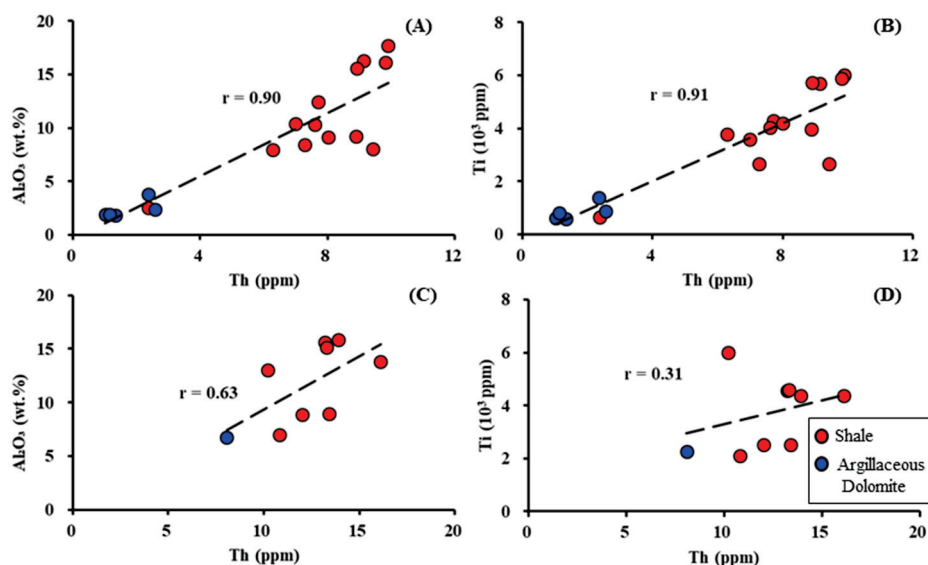


Figure 14. (A) Cross-plots of Th content versus Al₂O₃ content of well ZK17 samples in Chengkou; (B) cross-plots of Th content versus Ti content of well ZK17 samples in Chengkou; (C) cross-plots of Th content versus Al₂O₃ content of well ZK0305 samples in Xiushan; (D) cross-plots of Th content versus Ti content of well ZK0305 samples in Xiushan.

5.5. Uranium and Thorium Accumulation

The U–Th accumulation model can be established based on the above analysis and previous research on OM preservation in the Doushantuo Formation on the Upper Yangtze Platform [21,45,86,106–108] (Figure 15A–D). The surficial U and Th geochemical cycle involves several processes: weathering separates insoluble U (IV) and Th (IV) from parent rocks, oxidation converts insoluble U (IV) to soluble U (VI), atmospheric precipitation and river systems deliver soluble U (VI) and insoluble Th (IV) to the ocean, various geochemical marine processes remove U (VI) from seawater and deposit it into sediments, and Th (IV) is directly deposited in sediments (Figure 15) [5,82]. Authigenic precipitation, terrigenous input and hydrothermal input supplied the original U and Th inputs to the Doushantuo Formation (Figure 15). During the deposition of black shale in the Upper Yangtze Platform, such as in Z₁d₂ and Z₁d₄, the water depth increased due to the influence of transgression, and the reducing conditions in the depositional environment strengthened (Figure 15A,C). Many studies have reported predominantly suboxic–anoxic conditions during the deposition of the Doushantuo Formation, which is consistent with the findings of this study [45,86,106,107]. Anoxic or euxinic depositional environments can reduce dissolved U (U (VI)) to form less soluble UO₂ (U (IV)), i.e., authigenic U [7,66]. The relatively high paleoproductivity during the deposition of the Doushantuo Shales favored the preservation of OM (Table S1 and Figure 8) [45]. U dissolved in the bottom water can pass through the water–sediment surface and form uranyl–organometallic complexes in the sediments, which is beneficial for U accumulation [21,28]. In addition, a portion of U is enriched in the in-source solid bitumen that formed from the thermal cracking of the retained oil, resulting in elevated levels of U in the black shales (Figure 15D) [59]. The Th was deposited with terrigenous input and adsorbed by clay minerals in the form of small Th-containing minerals in the shales [101]. During the deposition of argillaceous dolomites, such as in Z₁d₃, the sea level fell due to tectonic movements (Figure 15B) [108]. Increased oxygen levels in the water column may have led to reactivation and redissolution of U (Figure 15D). A decrease in paleoproductivity is also not favorable for the adsorption of U

by OM (Table S1 and Figure 8). For Th, the low terrigenous input and low clay mineral content in the argillaceous dolomite results in a low Th content (Table S1, Figures 6 and 8). The Z_1d_2 and Z_1d_4 were deposited in the main depositional periods of the black shales in the study area [43], with higher U–Th contents than the Z_1d_3 dolomites. The Z_1d_2 black shale is more widely distributed and thicker than the Z_1d_4 black shale is, indicating that Z_1d_2 is a potential helium source in the Upper Yangtze Platform.

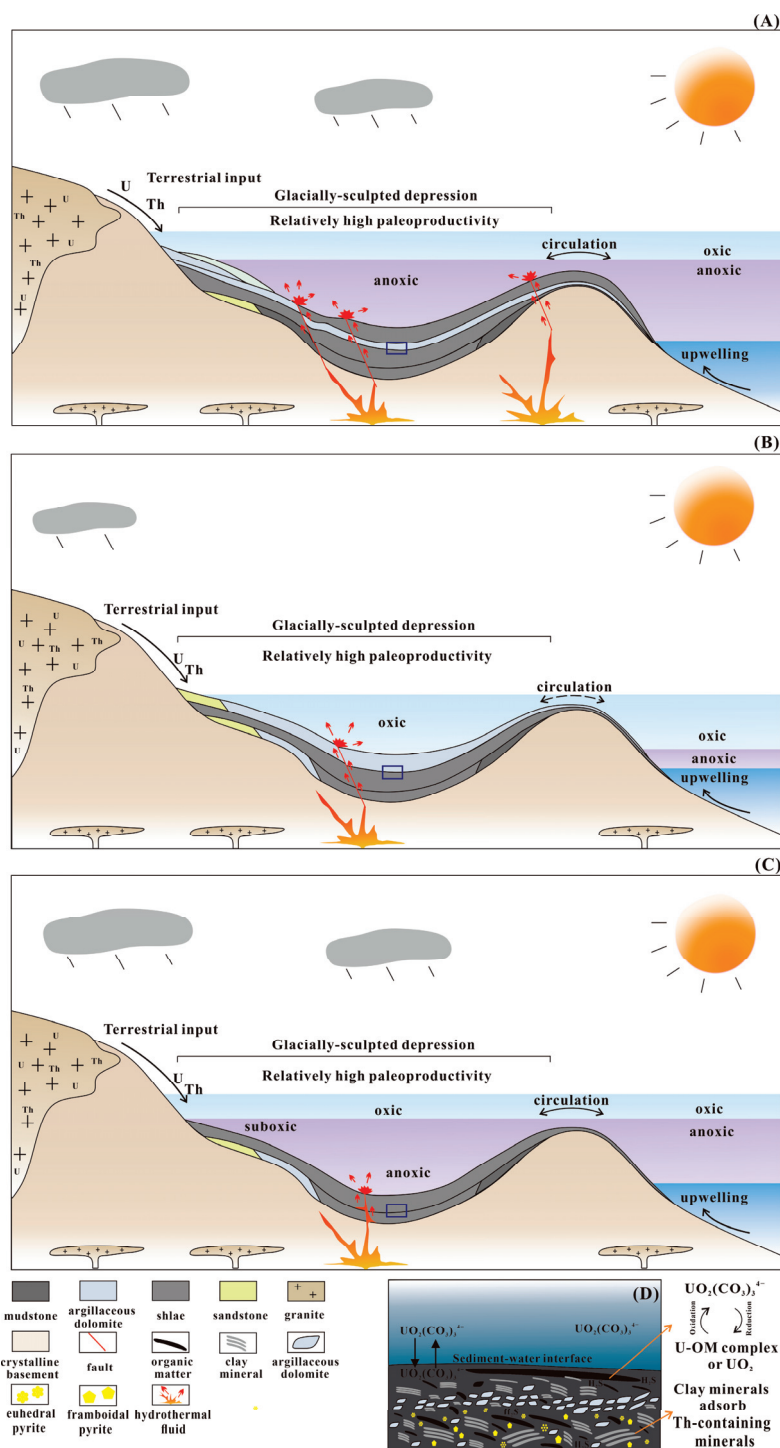


Figure 15. A model of the sedimentary evolution and U–Th accumulation model of the Doushantuo Formation in the Upper Yangtze Platform; (A) sedimentary evolution of Z_1d_4 ; (B) sedimentary evolution of Z_1d_3 ; (C) sedimentary evolution of Z_1d_2 (modified from Xiao, Cao, Luo, Tan, Xiao, He and Li [45]); and (D) U and Th micro accumulation patterns; the boxes in Figure (A–C) represent Figure (D).

5.6. Helium Production Potential from Black Shale

Shale rich in U and Th has a greater capacity of helium generation than that of granite and carbonate rock [24]. Helium has been found in the shale gas of the Wufeng-Longmaxi Formation in the Sichuan Basin, China, with concentrations ranging from 0.015 to 0.13% (mean of 0.039%) [109]. It is universally thought that the helium in shale gas tends to be primarily formed through the decay of the U and Th contained in the shale [10]. The average of U and Th contents in the Wufeng-Longmaxi shales is 10.4 ppm and 15.1 ppm [110–113], and the average of U and Th contents in the Doushantuo shales is 17.58 ppm and 9.78 ppm, respectively. The age of the Doushantuo Formation ranges from 635 to 560 Ma, which is older than the Wufeng–Longmaxi Formation (444 Ma). Thus, the Doushantuo shales have a great helium-generating capacity. Meng, et al. [114] found a relatively high content of helium (1.2%) in the shale gas of the Doushantuo Formation, which meets the criteria in industrial extraction. The $^3\text{He}/^4\text{He}$ ratios in the shale gas ranging from 0.009 to 0.010 Ra ($R_a = 1.4 \times 10^{-6}$) indicate that the helium in the shale gas is predominantly of crustal origin, which is mainly formed by the decay of U and Th in the shale.

The average age of the Doushantuo Formation is estimated to be 5.98×10^8 years (560–635 Ma). The shale distribution area of the Doushantuo shales in the Upper Yangtze Platform is $4.02 \times 10^{11} \text{ m}^2$, and the average thickness of shale is 46.5m [47,115]. Applying the cited helium generation formula, the total amount of helium (^4He) generated over the course of the geological history in the Doushantuo shales is calculated to be $7.12 \times 10^{10} \text{ m}^3$. Accordingly, the Doushantuo shales exhibit a considerable potential for helium production. Meanwhile, the potential for helium resource exploration can also be seen as significant in the Doushantuo shale gas.

6. Conclusions

- (1) The average U and Th concentrations in black shales (17.58 ppm and 9.78 ppm, respectively) are significantly higher than those in argillaceous dolomites (3.52 ppm and 2.75 ppm, respectively). The average values of CIA (60.57), CIW (75.54), PIA (68.44) and Rb/Sr (0.70) suggest a semi-humid climate and intermediate chemical weathering in the provenance area. Atmospheric precipitation and river systems can deliver soluble U (VI) and insoluble Th (IV) into the ocean, but excessive terrigenous input may dilute the U and Th contents in the formation. The high proportion of authigenic U in the total U content—39% in shales and 84% in argillaceous dolomites—indicates that authigenic U is a significant source of U in the Doushantuo Formation. In addition, the average δEu values in shales (1.20) and argillaceous dolomites (1.16) indicate that hydrothermal input was prevalent during the deposition of the Doushantuo Formation, contributing both U and Th to the system.
- (2) The positive correlation between U and TOC ($r = 0.95$) indicates that U in black shale is mainly adsorbed and/or complexed by OM (such as in-source solid bitumen). A relatively high abundance of OM benefits U accumulation ($\text{TOC} = 0.06\text{--}34.58 \text{ wt.}\%$). Redox conditions control the reduction in U (VI) and U adsorption and complexation by organic matter, as indicated by the positive relationships between U content and U/Th and Ni/Co ratios ($r = 0.91$ and 0.85 , respectively). The Th accumulation mechanism differs from that of U, and it is mainly controlled by clay minerals, evidenced by a positive correlation between Th content and clay minerals ($r = 0.67$).
- (3) The Doushantuo shales exhibit a higher potential for helium production than argillaceous dolomites due to their higher U and Th concentrations. Therefore, the Doushantuo shale gas is a promising target for helium resource exploration. The total amount of helium generated in the Doushantuo Shales is estimated to be $7.12 \times 10^{10} \text{ m}^3$.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse13030413/s1>, Table S1: Chemical and mineral compositions of the Doushantuo Formation in the Upper Yangtze Platform; Table S2: Correlation coefficients of U content, Th content and major element content, trace element content, and TOC in shales; Table S3: Correlation coefficients of U content, Th content and major element content, trace element content, and TOC in argillaceous dolomites; Table S4: The contents of clay minerals in the shales.

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Article

Facies-Controlled Sedimentary Distribution and Hydrocarbon Control of Lower Cretaceous Source Rocks in the Northern Persian Gulf

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Abstract: The two-phase source rocks deposited during the Lower Cretaceous in the Persian Gulf Basin play a pivotal role in the regional hydrocarbon system. However, previous studies have lacked a macroscopic perspective constrained by the Tethyan Ocean context, which has limited a deeper understanding of their developmental patterns and hydrocarbon control mechanisms. To address this issue, this study aims to clarify the spatiotemporal evolution of the two-phase source rocks and their hydrocarbon control effects, with a particular emphasis on the critical impact of terrestrial input on the quality improvement of source rocks. Unlike previous studies that relied on a single research method, this study employed a comprehensive approach, including time series analysis, sequence stratigraphy, lithofacies, well logging, well correlation, seismic data, and geochemical analysis, to systematically compare and analyze the depositional periods, distribution, and characteristics of the two-phase source rocks under different sedimentary facies in the region. The goal was to reveal the intrinsic relationship between the Neo-Tethyan Ocean context and regional sedimentary responses. The results indicate the following: (1) the late Tithonian–Berriasian and Aptian–Albian source rocks in the Northern Persian Gulf were deposited during periods of extensive marine transgression, closely aligning with the global Weissert and OAE1d anoxic events, reflecting the profound impact of global environmental changes on regional sedimentary processes; (2) in the early stages of the Neo-Tethyan Ocean, controlled by residual topography, the Late Tithonian–Berriasian source rocks exhibited a shelf–intraself basin facies association, with the intraself basin showing higher TOC, lower HI, and higher Ro values compared to the deep shelf facies, indicating more favorable conditions for organic matter enrichment; (3) with the opening and deepening of the Neo-Tethyan Ocean, the Aptian–Albian source rocks at the end of the Lower Cretaceous transitioned to a shelf–basin facies association, with the basin facies showing superior organic matter characteristics compared to the shelf facies; (4) the organic matter content, type, and thermal maturity of the two-phase source rocks are primarily controlled by sedimentary facies and terrestrial input, with the Aptian–Albian source rocks in areas with terrestrial input showing significantly better quality than those without, confirming the decisive role of terrestrial input in improving source rock quality. In summary, this study not only reveals the differences in the depositional environments and hydrocarbon control mechanisms of the two-phase source rocks, but also highlights the core role of terrestrial input in enhancing source rock quality. The findings provide a basis for facies selection in deep natural gas exploration in the Zagros Belt and shale oil exploration in the western Rub’ al-Khali Basin, offering systematic theoretical guidance and practical insights for hydrocarbon exploration in the Persian Gulf and broader tectonic domains.

Keywords: anoxic events; sequence stratigraphy; Neo-Tethys Ocean; terrestrial input; hydrocarbon generation

1. Introduction

The Persian Gulf, located in the western Asian segment of the Tethyan domain, is part of the Arabian Plate. It comprehensively records the entire process of the opening and evolution of the Proto-Tethyan Ocean, Paleo-Tethyan Ocean, and Neo-Tethyan Ocean [1]. This region not only formed the Paleo-Tethyan hot shales, but also developed Lower Cretaceous source rocks under the evolution of the Neo-Tethys Ocean [2]. During this evolutionary process, not only were the hot shales of the Paleo-Tethyan Ocean period formed, but high-quality Lower Cretaceous source rocks were also developed under the evolution of the Neo-Tethyan Ocean [3]. The multiple marine transgression events of the Tethyan Ocean (e.g., the Silurian hot shales, influenced by global large-scale transgressions, exhibit macroscopically uniform distribution characteristics) have resulted in significant spatiotemporal evolutionary features of the source rocks within the region [2,4]. During the opening stage of the Neo-Tethyan Ocean, the Arabian region experienced multiple marine transgressions in the Cretaceous, leading to the formation of two phases of source rocks: the Late Tithonian–Berriasian and Aptian–Albian of the Lower Cretaceous.

These two phases of source rocks are widely distributed in the Northern Persian Gulf, characterized by high organic matter abundance, and serve as the core source rocks of the regional hydrocarbon system. Previous studies have conducted extensive research on them, indicating that the sedimentary facies and tectonic background of the Early Cretaceous source rocks in the Northern Persian Gulf are crucial factors controlling the preservation of organic matter, the evolution of maturity, and subsequent hydrocarbon generation [4–10]. Meanwhile, numerous scholars have demonstrated the influence of sedimentary environments on organic matter types and maturity through organic geochemical parameters, providing a quantitative basis for the evaluation of source rocks [11–29].

Although previous studies have conducted detailed localized research on the two phases of source rocks (Late Tithonian–Berriasian and Aptian–Albian) in the Persian Gulf region, such as in the East Baghdad, Darquain, Nasiriya, Dukhan, and Halfaya oil fields, there remains a lack of comprehensive understanding regarding the regional differences in the depositional distribution and hydrocarbon generation characteristics of these two phases of source rocks during the evolution of the Neo-Tethyan Ocean [11–29]. Existing literature primarily focuses on localized sedimentary facies and hydrocarbon exploration case studies, lacking a systematic explanation of the synergistic effects of transgression events, terrestrial input, and sedimentary facies belts on the formation and spatial distribution of source rocks within the overall evolutionary framework of the Neo-Tethyan Ocean.

To address the aforementioned issues, this study built on previous measured data and employed comprehensive methods such as high-resolution sequence stratigraphy, lithofacies analysis, and biofacies assemblage modeling. Unlike previous research that focused solely on localized oil fields, this study constructed a sequence model encompassing the main sedimentary facies belts within the region, enabling a multi-scale, multi-method-integrated analysis from local to regional scales. The aim was to systematically explore the sedimentary characteristics and hydrocarbon generation patterns of the two phases of source rocks during the evolution of the Neo-Tethyan Ocean in the Persian Gulf region and to reveal the main controlling factors influencing the quality and distribution of source rocks. The findings can provide a basis for facies selection in deep natural gas exploration

in the eastern margin of the Arabian Plate (Zagros Belt) and shale oil exploration in the western margin (Rub' al-Khali Basin), thereby offering systematic theoretical guidance and practical insights for hydrocarbon exploration in the Persian Gulf and broader tectonic domains. Based on this, the following hypotheses are proposed:

- (1) The two phases of source rocks in the Persian Gulf region exhibit significant differences in depositional environments, lithofacies types, and associations;
- (2) Multiple transgression events during the evolution of the Neo-Tethyan Ocean played a decisive role in the organic matter enrichment and spatial distribution of the source rocks;
- (3) The input of terrestrial materials and the synergistic effects of sedimentary facies belts jointly control the hydrocarbon generation potential of the source rocks in the region.

2. Geological Background

The Persian Gulf Basin is located at the convergence of the Arabian Plate and the Eurasian Plate, situated at the edge of the ancient Neo-Tethys Ocean. From the source area to the depositional area, it can be divided into three major geological units: the stable Arabian Shield in the west, the stable Arabian Platform in the center, and the Zagros Foreland Deformation Zone in the east [29] (Figure 1a). In addition, the northern passive marginal basin consists of the Western Arabian Basin, the Widiyan-Mesopotamian Basin, the Central Arabian Basin, and the Rub' al-Khali Basin [29]. The northward unidirectional subduction of the Neo-Tethyan Ocean and multiple phases of continental block collisions led to the formation of basement rift zones, passive continental margins, and foreland basins. These tectonic processes controlled the evolution of sedimentary environments and laid the foundation for the subsequent development of source rocks [2,29]. The basin is filled with sediments ranging from the Paleozoic to the Cenozoic, with the Paleozoic dominated by clastic rocks and the Mesozoic to Cenozoic primarily composed of marine carbonate rocks. During this evolutionary process, two critical phases of source rock deposition were formed:

- (1) Late Jurassic–Early Cretaceous (Late Tithonian–Berriasian, approximately 129–140 Ma).

During this period, the Sarmord and Chia Gara formations correspond to the Diyabakir and Kirkuk regions, the Garau and Yamama formations to the Lorestan region, and the lower Fahliyan Formation to the Khuzestan and Fars regions. The lithology is dominated by micritic limestone and calcareous shale, with GR curves showing high-amplitude serrated patterns, reflecting anoxic-high productivity environments in intrashelf basins. The back-arc extension during the initial expansion of the Neo-Tethyan Ocean (~145 Ma) caused differential subsidence along the northern margin of the Arabian Plate, forming multiple isolated intrashelf basins that provided closed conditions for organic matter preservation (average TOC of 4–5%). The early stage featured *Pterocera* from the Late Jurassic, while the late stage included *Watznaueria barnesae* and *Haqius circumradius* from the Berriasian [12], which contributed abundant organic matter for the formation of source rocks.

- (2) Late–Early Cretaceous (Aptian–Albian, approximately 90–110 Ma)

During this stage, sedimentation was concentrated in the Mesopotamian Foredeep (Nahr Umr Formation) and the Fars Platform margin. The lithofacies association is characterized by deep-water slope facies, including argillaceous sandstone and siliceous nodular limestone. Bioturbation structures and pyrite enrichment indicate a bathyal reducing environment. Key biomarkers include *Biticinella berggensis* [8] and diverse ammonoid fauna [14], which provided the material basis for the formation of high-quality source rocks and reservoirs. The organic matter is predominantly Type II kerogen, with TOC reaching up to 12%.

The unidirectional subduction of the Neo-Tethyan Ocean and multiple phases of continental block collisions regulated the formation of basement rift zones and basin types. By controlling sediment supply and depositional environments, these tectonic processes influenced the lithology and sequence evolution of the two depositional stages. The transgression events triggered by tectonic movements altered sedimentary facies and material input, leading to significant differences in lithology and sequences between the Late Tithonian–Berriasian and Aptian–Albian stages. These differences in depositional environments and lithology are directly reflected in the organic matter enrichment and spatial distribution of the source rocks, providing critical insights for regional hydrocarbon generation and exploration.

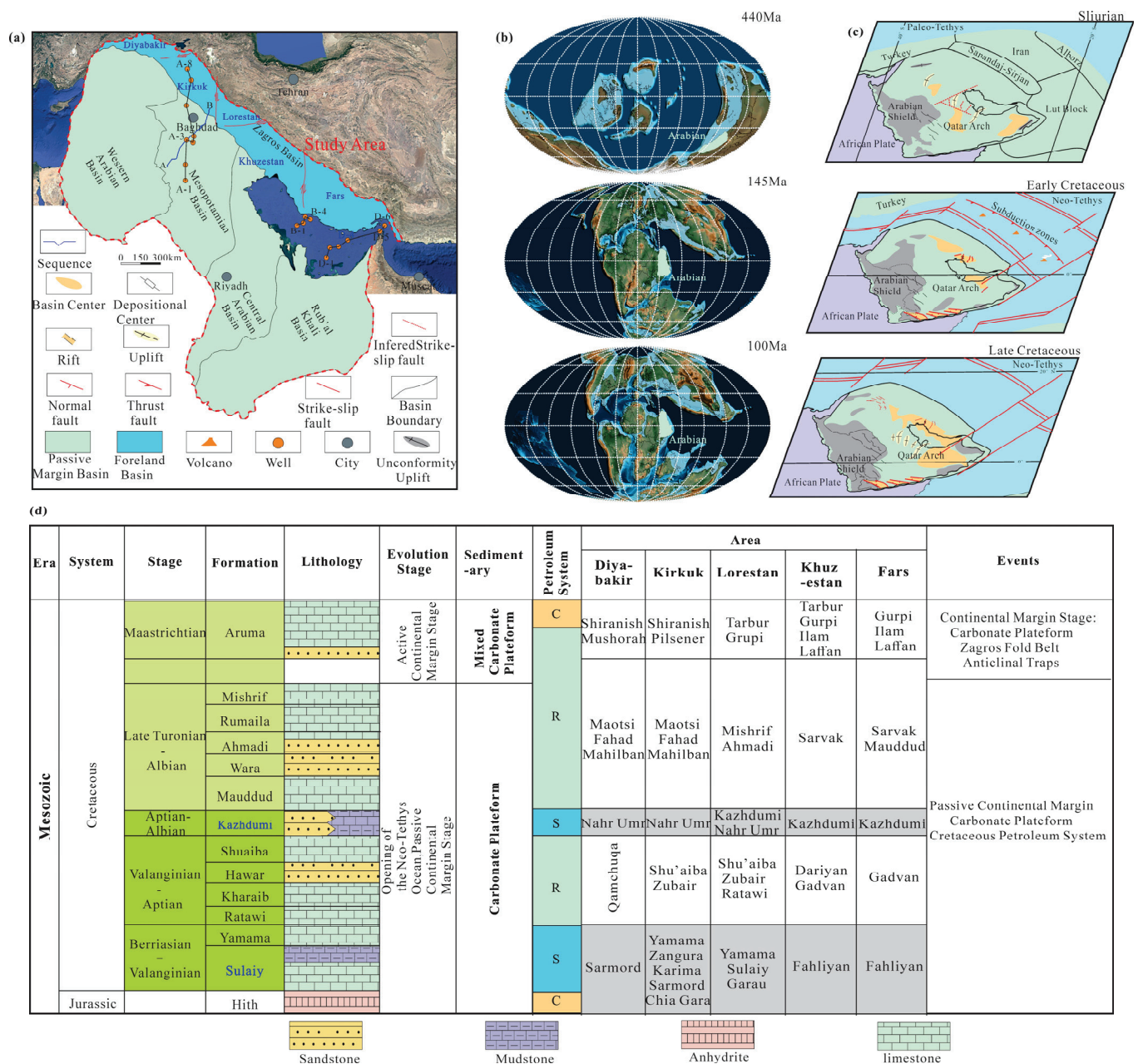


Figure 1. (a) Study area in the northern of the Persian Gulf (the study area is marked, along with the locations of the wells and seismic profiles shown below). (b) Plate positions of Arabia at different periods (the positions of the Arabian plate in different periods have been indicated) [30]. (c) Intraplate evolution of Arabia at different periods [31]. (d) Stratigraphic column of the study area in the northern of the Persian Gulf.

3. Materials and Methods

This study adopted the official units of the International Commission on Stratigraphy (ICS), dividing the Cretaceous into two series and twelve stages. The target intervals were located in the Early Cretaceous Late Tithonian–Berriasian and Aptian–Albian stages. Based on the paleogeographic reconstructions by Christopher R. Scotese using the Mollweide projection of GIS software (ArcMap 10.8.2, ESRI, Redlands, CA, USA) [22] (Figure 1b) and the Arabian Plate evolution reconstructed by Niu Binbin et al. [31] (Figure 1c), the internal tectonic and depositional settings of the Arabian Plate during the unidirectional subduction of the Neo-Tethyan Ocean were clarified.

The data collection and organization for this study primarily include data from multiple research wells within the region and publicly available database resources. Sampling points involve wells such as D-4 and A-3, (Resform, Version 5.1) with well locations shown in Figure 1. Seismic data were independently acquired, and the profile locations are illustrated in Figure 1. Geochemical data were mainly sourced from English-language publications and the HIS database [1,8,11,12,14,15,17–19,22–28,32–39]. The data cover literature and datasets were published between 1990 and 2024, with selection criteria including complete sampling information, well-documented instrument calibration records, and peer-reviewed recognition (specific data ranges are provided in Supplementary Table S1). To ensure the scientific identification of depositional sequences and hydrocarbon-bearing boundaries, the following methods were employed: high-resolution stratigraphic analysis: Acycle (Version 2.7) was used to perform high-precision stratigraphic division of the Lower Cretaceous time series from Well D-4, with a detailed recording of the sampling and temporal parameters. Seismic data analysis: for seismic data from Well A-3 (Petrel, Version 2018), reflection amplitude, frequency variation, and continuity analysis were applied to identify seismic interfaces, flooding surfaces, and maximum flooding surfaces. Sequence stratigraphy and corresponding hydrocarbon-bearing boundaries were determined through comparative analysis. Lithofacies classification: based on well log descriptions, reflection internal structures, and well correlation profiles, lithofacies were classified for different depositional environments.

For the geochemical analysis of the two-phase source rocks in the region, the following steps were taken. (1). Data collection and parameter determination: data from well samples, including TOC, HI, OI, Tmax, Ro, and S1+S2, were collected. The measurement ranges for these parameters were as follows: TOC 0–4%, HI 50–600 mg/g, Tmax 420–500 °C, and Ro 0.6–3% (2). Data organization and chart generation: the collected source rock characteristic indicators were systematically organized based on different facies and lithologies. Charts reflecting depositional environments and source rock distribution patterns were generated, including C27–C29 ternary diagrams, HI-OI cross-plots, pristane-phytane cross-plots, as well as HI-Tmax, NA-TOC, and S2-TOC cross-plots to identify organic matter types, maturity, and quality. Through chart comparison, the differences in depositional environments and hydrocarbon control mechanisms between the Late Tithonian–Berriasian and Aptian–Albian stages were clarified.

This study ensured the completeness and reliability of data sources, providing a structured and reproducible experimental workflow for depositional sequence analysis, lithofacies classification, and source rock evaluation. Detailed information (e.g., sampling data, specific parameter ranges, depositional sequence identification, and lithofacies classification criteria) offers a solid foundation for subsequent research, enhancing the rigor of the methodology and the reproducibility of the experiments.

4. Results and Discussion

4.1. Climate Evolution and Determination of Hydrocarbon Generation Periods Following the Formation of the Neo-Tethys Ocean

During the Lower Cretaceous, the Neo-Tethys Ocean was in a continuous subduction phase beneath the Eurasian Plate [40], leading to the rapid growth of oceanic crust. An intra-oceanic subduction zone developed within the Arabian Plate, accompanied by intensified magmatic activity and extensive volcanic eruptions. The CO₂ released from these eruptions contributed to a greenhouse effect [41], resulting in higher sea surface temperatures. The warm and humid conditions during this greenhouse period promoted biodiversity [42]. By identifying and tracing sequences and flooding surfaces on seismic interfaces from Well A-3, the hydrocarbon generation environments of the two source rock intervals were further clarified. Both the Aptian–Albian and Late Tithonian–Berriasian source rocks were deposited during periods of sea-level rise, corresponding to the regressive cycles of third-order sequences (Figure 2). Onlap and the most distal onlap points were observed within the source rock intervals, while downlap was evident in the overlying strata. Additionally, anomalous shifts in $\delta^{13}\text{C}$ [31,33,40] (Figure 2) indicate significant carbon burial events associated with rapid sea-level rise [33], suggesting that both source rock intervals were deposited during extensive marine transgressions, providing a favorable foundation for the formation of source rocks (Figure 2).

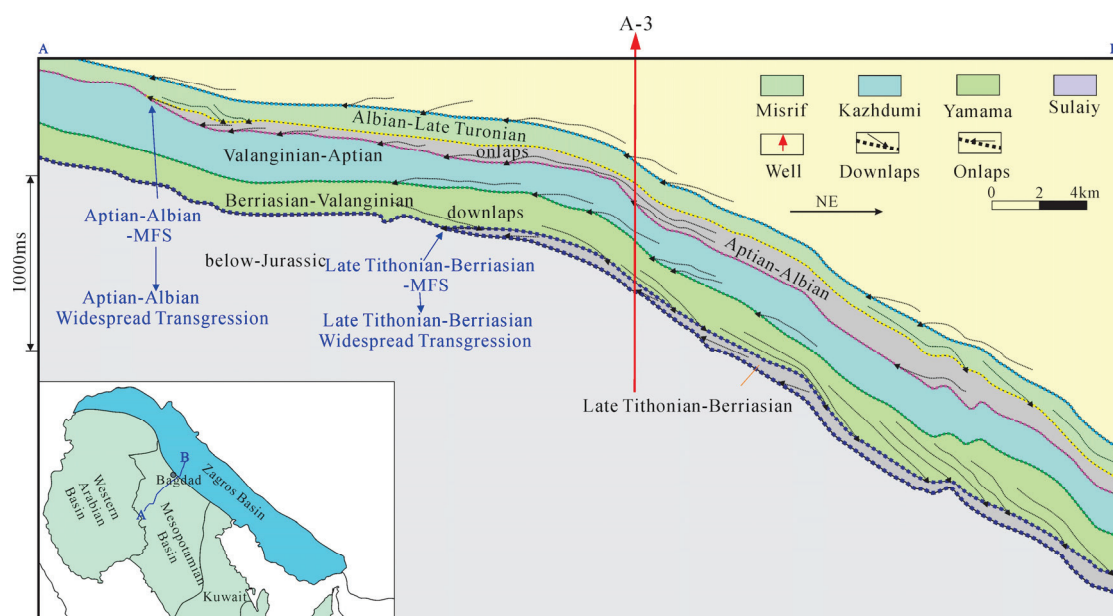


Figure 2. Sequence framework of the source rocks and the two marine transgressions (Late Tithonian–Berriasian and Aptian–Albian stages). The locations of the profiles and the occurrences of overriding/underlying units are indicated in the figure. Different colors represent stratigraphic units deposited during different periods, and the two source rock intervals are shown in shades of gray).

The deposition of source rocks in the study area was influenced by various astronomical orbital parameters. This study utilized Acycle to analyze the time series of the Cretaceous in Well D-4, identifying two favorable source rock intervals in the north of the Persian Gulf during the Lower Cretaceous: the Late Tithonian–Berriasian stage (129–140 Ma) and the Aptian–Albian stage (approximately 97 Ma). These intervals exhibited good synchronicity with the Weissert anoxic event and the OAE1d anoxic event of the Cretaceous, consistent with previous studies [26,43,44] (Figure 3). During anoxic events, the bottom water became oxygen-depleted, while the surface water exhibited high productivity, reflecting the climatic evolution of the Lower Cretaceous and establishing a strong correlation with sea-level

changes. This provides robust evidence for the evolutionary background of the source rocks and highlights the contribution of anoxic events to their formation.

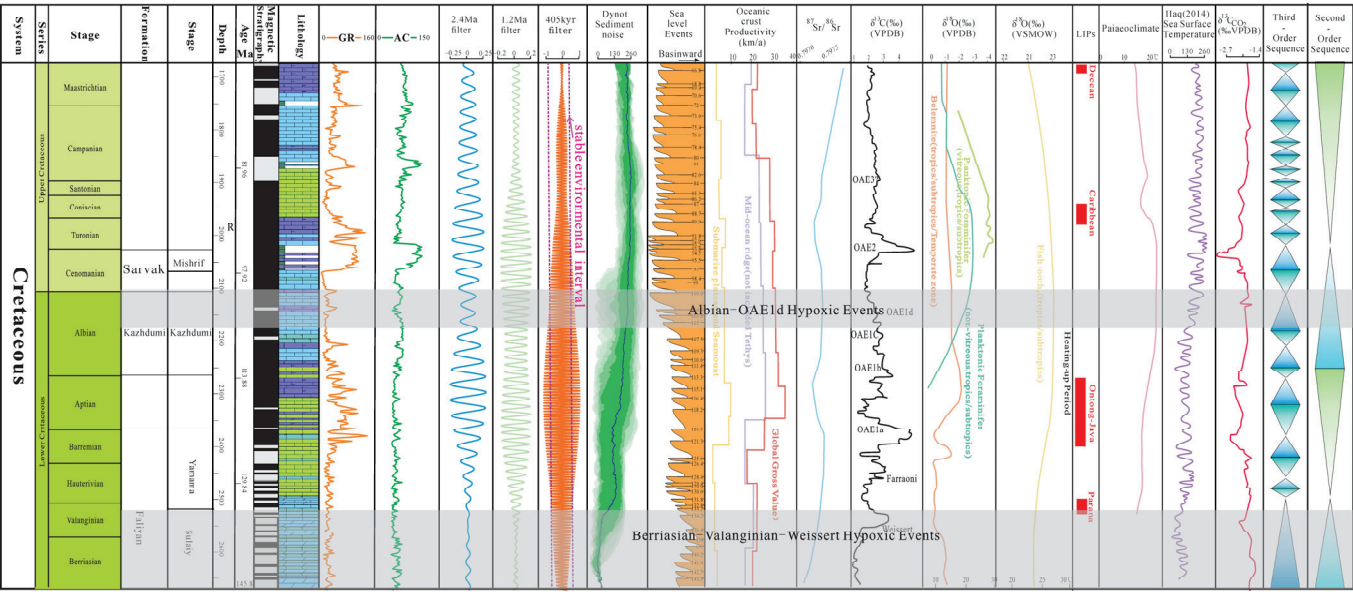


Figure 3. Determination of hydrocarbon generation periods for the source rocks (Late Tithonian–Berriasian and Aptian–Albian stages, modified from references [45,46]).

4.2. Evolution of the Neo-Tethys Ocean and Paleogeographic Filling Patterns

During the Late Tithonian–Berriasian stage, the Neo-Tethys oceanic crust subducted in a northeastward direction beneath the Eurasian Plate, resulting in significant differential subsidence in the Mesopotamian Basin of Iraq and southwestern Iran [47]. This subsidence led to the separation of the Arabian Plate from the Taurides and Batlis microcontinental blocks. These microblocks, located in the northeastern part of the Arabian Plate, were tectonically connected to the western block of the Arabian Plate, which inherited the Triassic Rutba Uplift and Mosul High [47]. In eastern Oman, a narrow deep-sea zone filled with clastic sediments developed, transitioning westward into a narrower intermediate zone, and further west into the Mesopotamian Basin, which was characterized by a broad shallow-water carbonate depositional area. The Arabian Plate exhibited relatively confined tectonic features, forming a differential subsidence pattern with a restricted western region and a broad, gentle eastern region. This differential subsidence pattern dominated the regional depositional framework, particularly influencing the depositional centers of the Late Tithonian–Berriasian stage. During this period, three main depositional centers were distributed, showing distinct east–west isolation in space, with depositional environments including shallow shelf, deep shelf, and intrashelf basin facies (Figure 4a), indicating significant spatial variations in depositional environments. In the restricted western environment, the development of intrashelf basins was prominent, primarily filled with argillaceous limestone. The well correlation profile from Well B-1 to Well B-4 (Figure 4g) mainly includes deep shelf and intrashelf basin facies, where the deep shelf lithology is dominated by pack-stone (Figure 4b,c), and the intrashelf basin is characterized by mudstone (Figure 4d,e). The well correlation profile from Well D-1 to Well D-6 (Figure 4f) includes shallow shelf, deep shelf, and intrashelf basin facies. The shelf lithology is rich in dolomite, indicating a warm and humid shallow marine environment. Based on the E–F seismic profile (Figure 4h), the Late Tithonian–Berriasian shelf environment is characterized by low-frequency, weak-amplitude, and poorly continuous high-energy conditions, with downlap phenomena observed in the overlying strata. In the G–H seismic profile (Figure 4i), the Late Tithonian–

Berriasian intrashelf basin is characterized by medium-frequency, medium-amplitude, and well-continuous low-energy conditions.

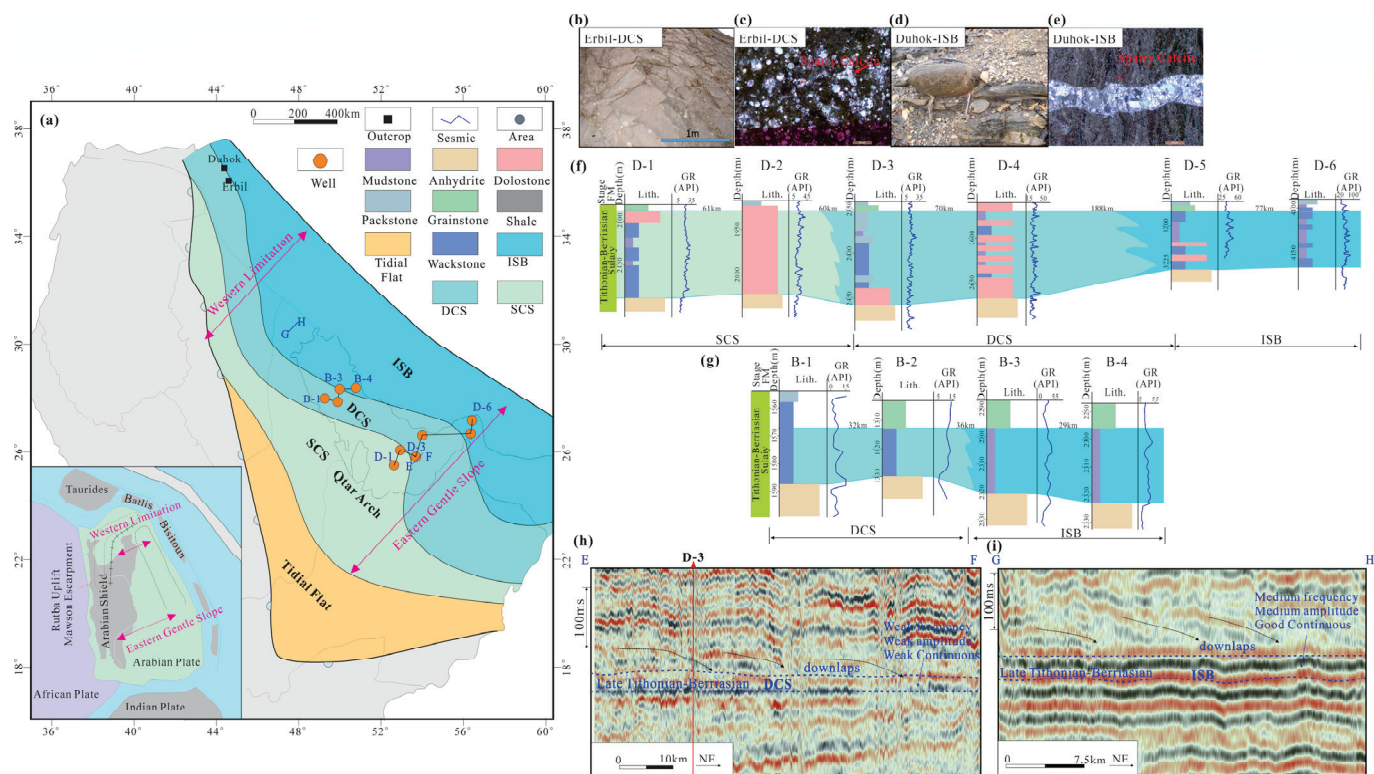


Figure 4. Sedimentary distribution of Late Tithonian–Berriasian source rocks. In (a), the lower left corner shows the intraplate evolution of the Arabian plate during the Late Tithonian–Berriasian, which is restricted in the west and gentle in the east. (b–e) From reference [13], (b,c) represent thin sections from different regions of DCS; (d,e) represent thin sections from different regions of ISB. SCS: shallow carbonate shelf; DCS: deep carbonate shelf; ISB: intrashelf basin. (f) Shallow shelf–deep shelf–intrashelf basin in Wells D-1 to D-6 of the Late Tithonian–Berriasian stage. (g) Deep shelf–intrashelf basin facies of Late Tithonian–Berriasian source rocks. (i): E–F seismic profile of the deep shelf. (h): G–H seismic profile of the intrashelf basin.

During the late Lower Cretaceous Aptian–Albian stage, the continental margin of the Arabian Plate experienced collapse, manifested by the southwestward retreat of the Rutba Uplift and Mosul High. From the perspective of tectonic evolution, the changes in the depositional framework during the late Lower Cretaceous were closely related to the retreat and subsidence of the Arabian Plate’s continental margin. The increase in coarse clastics from the Arabian Shield caused the shallow-water carbonate depositional area to shift eastward, while the migration of shelf carbonate depositional areas further offshore indicated an increased supply of terrigenous clastics. The shallow-water carbonate depositional area expanded, while the extent of coastal plain deposits decreased. This tectonic event led to a transformation in the overall depositional framework of the Arabian Plate, resulting in a broader and more uniform depositional environment, with more orderly distribution of depositional centers. The depositional centers of the Aptian–Albian source rocks exhibited a uniform distribution, with diverse sedimentary facies, including the western delta-influenced shelf–basin facies and the eastern non-influenced shelf–basin facies, primarily filled with mudstone and shale (Figure 5b–e). Based on lithofacies, the shelf area was dominated by argillaceous limestone and mudstone (Figure 5b,c), while the basin area was mainly composed of mudstone (Figure 5d,e). The well correlation profile from Well A-1 to Well A-8 (Figure 5f) includes shallow marine shelf and deep marine shelf

facies, with the shallow marine shelf primarily consisting of thick sandstone sequences and the deep marine shelf dominated by argillaceous limestone. The well correlation profile from Well D-1 to Well D-5 (Figure 5g) is mainly composed of basin facies, with lithofacies dominated by mudstone and shale (Figure 5). These changes indicate that the depositional environment of the Arabian Plate during the late Lower Cretaceous transitioned from a restricted depositional pattern to a more uniform and widespread depositional pattern.

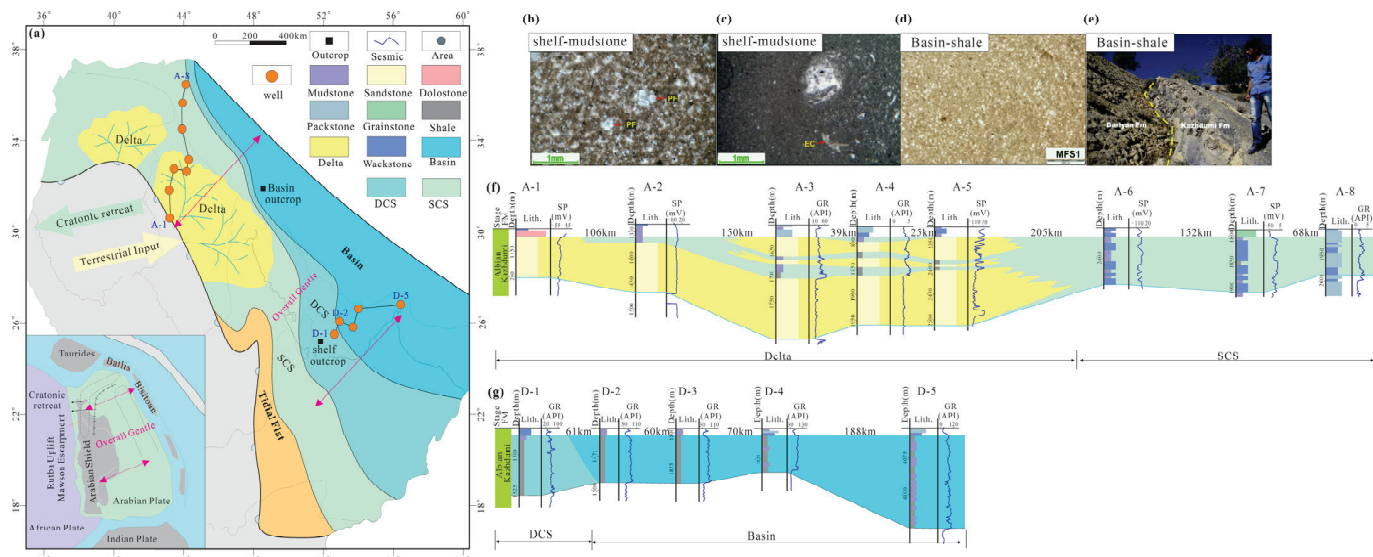


Figure 5. Sedimentary distribution of Aptian–Albian source rocks. In (a), the lower left corner shows the intraplate evolution of the Arabian plate during the Aptian–Albian, with a uniform east–west distribution. (b–e) From references, (b,c) represents shelf–mudstone thin sections; (d,e) represents basin–shale thin sections [21,48], (f) Well correlation profile from Well A-1 to Well A-8 showing delta–shallow shelf facies of Aptian–Albian source rocks. (g) Well correlation profile from Well D-1 to Well D-5 showing deep shelf–basin facies of Aptian–Albian source rocks.

In summary, the formation of the depositional centers during the Late Tithonian–Berriasian and Aptian–Albian stages is closely related to the differential subsidence, marine transgressions, and tectonic evolution of the Arabian Plate. The depositional environment in the region gradually transitioned from a restricted western depositional setting to a more uniform depositional pattern.

4.3. Distribution and Characteristics of Source Rocks

In a sedimentary basin, only effective source rocks can provide commercial hydrocarbon accumulations. To be considered effective, source rocks must contain sufficient organic matter, have favorable organic matter types, and undergo the process of organic matter transformation into hydrocarbons [49]. This study used total organic carbon (TOC) to describe the quantity of organic matter. For poor, fair, good, very good, and excellent source rocks, the TOC values are 0–0.5, 0.5–1, 1–2, 2–4, and greater than 4, respectively [50]. The hydrogen index (HI) was used to describe the type of kerogen. For Type III kerogen, HI ranges between 50 and 200, indicating a gas-prone nature and a marine depositional environment. For Type II kerogen, HI ranges between 200 and 600, indicating good oil and gas generation potential and a transitional marine–terrestrial depositional environment. For Type I kerogen, HI is greater than 600, indicating an oil-prone nature and a terrestrial depositional environment [50]. The vitrinite reflectance (R_o) is used to describe the thermal maturity of organic matter. R_o values between 0.6 and 1 indicate the oil generation window, values between 1 and 1.35 indicate the wet gas window, and values between 1.35 and 3 indicate the dry gas window.

The kerogen types in the Late Tithonian–Berriasian stage are mainly Type II and Type III. Comparing the organic matter abundance, kerogen type, and maturity indicators of the source rocks, mudstones showed relatively higher values compared to marlstones (Table S1). For Late Tithonian–Berriasian mudstones, the lowest TOC value was found in the Azadegan oilfield at 0.9%, with an HI of 157.18 mg/g. The highest TOC value was found in the Gashun oilfield at 19.16%, with an HI of 537.05 mg/g. For Late Tithonian–Berriasian marlstones, the lowest TOC value was found in the Ab-e Zimkan oilfield in the Lorestan segment at 0.19%, with an HI of 159.10 mg/g and Tmax of 418 °C. The highest TOC value was found in the Kushk oilfield in the Khuzestan segment at 4.52%, with an HI of 89.29 mg/g and Tmax of 441.57 °C. Mudstones were mainly developed in intrashelf basins, while marlstones were mainly developed on shelves.

For the Aptian–Albian source rocks, marlstones and mudstones were predominant. Mudstones were mainly developed in basins, while marlstones were mainly developed on shelves. Mudstones showed relatively higher values compared to marlstones. For Aptian–Albian mudstones, the lowest TOC value was found in the Mand oilfield at 0.09, with an HI of 377. The highest TOC value was found in the Marun oilfield at 4.99, with an HI of 323.24. For Aptian–Albian marlstones, the lowest TOC value was found in the Kuh-e Khaki oilfield at 0.19, with an HI of 355. The highest TOC value was found in the Farur oilfield at 2.03, with an HI of 158. Evaluation indicators of source rocks during the Late Tithonian–Berriasian and Aptian–Albian are hydrocarbon generation periods (see Supplementary Material Table S1).

During the Late Tithonian–Berriasian stage, with the opening of the Neo-Tethys Ocean, the study area lacked terrigenous input, and the depositional differentiation was influenced by residual paleo-highs, resulting in a suite of shelf–intrashelf basin source rocks. By the late Lower Cretaceous Aptian–Albian stage, water depth increased, and paleo-continentals retreated, leading to a broad and uniform depositional environment in the study area. The input from the western delta caused depositional differentiation, resulting in a suite of shelf–basin source rocks, with terrigenous-influenced source rocks in the west and non-terrigenous-influenced source rocks in the east.

The distribution maps of Late Tithonian–Berriasian source rock indicators show that high TOC values were mainly distributed in intrashelf basins, with maximum values exceeding 4, and three high-value evolution centers. Shallow and deep shelves were dominated by TOC values of 0–1. High HI values were mainly distributed in intrashelf basins and deep shelves, with two thermal evolution centers. Intrashelf basins had lower HI values than deep shelves, indicating a marine environment. Ro values ranged from 0.4 to 1.0, indicating that most of the source rocks were within the oil generation window, with higher maturity in intrashelf basins, reflecting the contribution of burial depth to their thermal evolution (Figure 6a).

The distribution maps of Aptian–Albian source rock indicators show that high TOC values are mainly distributed in basin facies, with maximum values exceeding 4. Shelf facies had TOC values of 2.0–3.0, indicating lower organic matter content compared to basin facies. High HI values were mainly distributed in shelf facies, with a maximum value of 400, indicating a transitional marine–terrestrial environment. Ro values ranged from 0.4 to 1.0, indicating that most of the source rocks were within the oil generation window, with higher maturity in basin facies, reflecting the contribution of burial depth to their thermal evolution (Figure 6b). The distribution of TOC, HI, and Ro in Late Tithonian–Berriasian and Aptian–Albian source rocks indicates facies-controlled constraints.

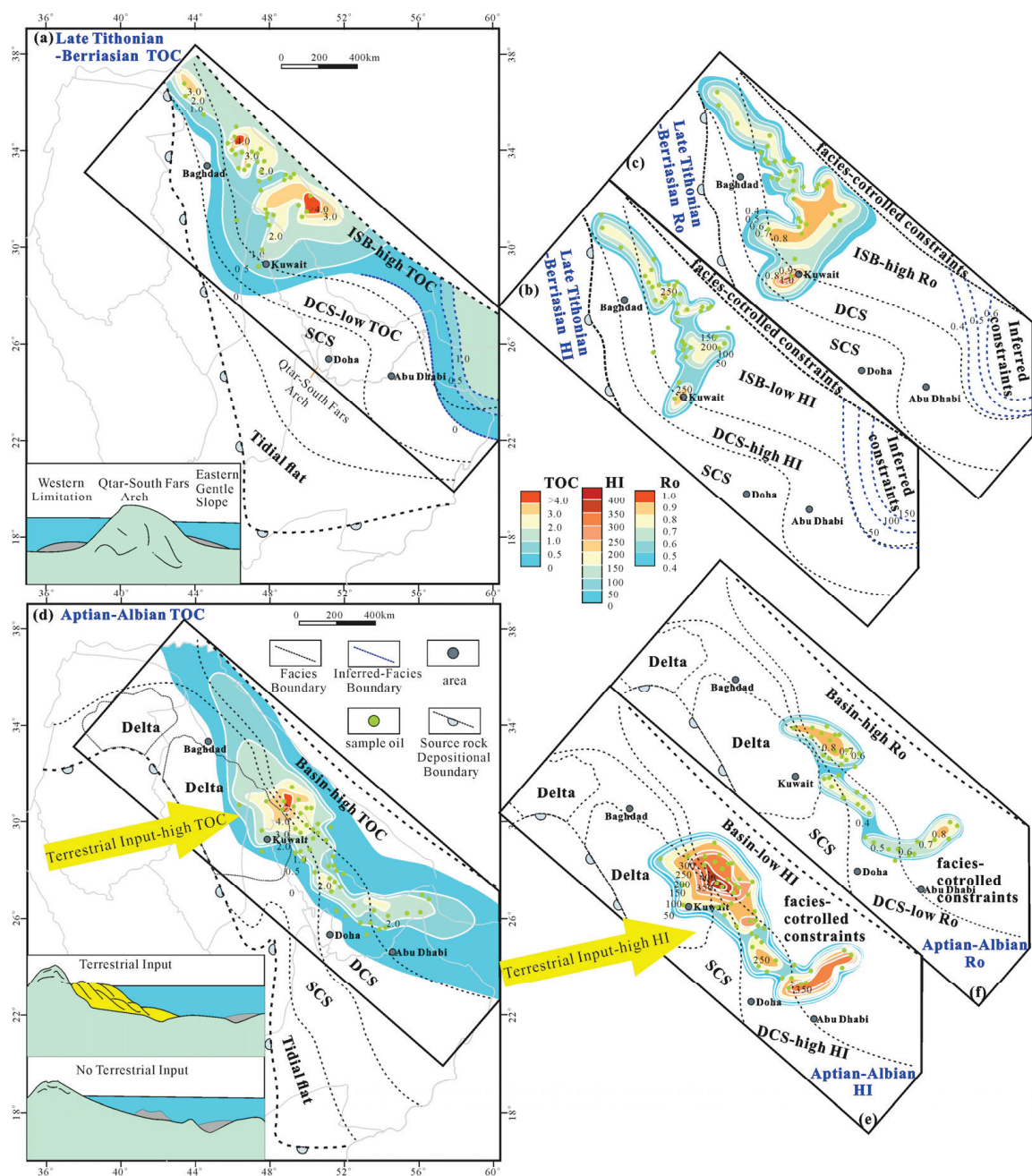


Figure 6. Distribution maps of TOC, HI, and Ro for Late Tithonian–Berriasian and Aptian–Albian source rocks: (a) TOC distribution map for the Late Tithonian–Berriasian stage; (b) HI distribution map for the Late Tithonian–Berriasian stage; (c) Ro distribution map for the Late Tithonian–Berriasian stage; (d) TOC distribution map for Aptian–Albian source rocks; (e) HI distribution map for Aptian–Albian source rocks; (f) Ro distribution map for the Late Tithonian–Berriasian stage.

The C^{27} , C^{28} , and C^{29} sterane ternary diagram, pristane–phytane cross-plot, and HI–OI cross-plot indicate a deepening of the water environment from the Late Tithonian–Berriasian shelf–intraself basin to the Aptian–Albian shelf–basin (Figure 7).

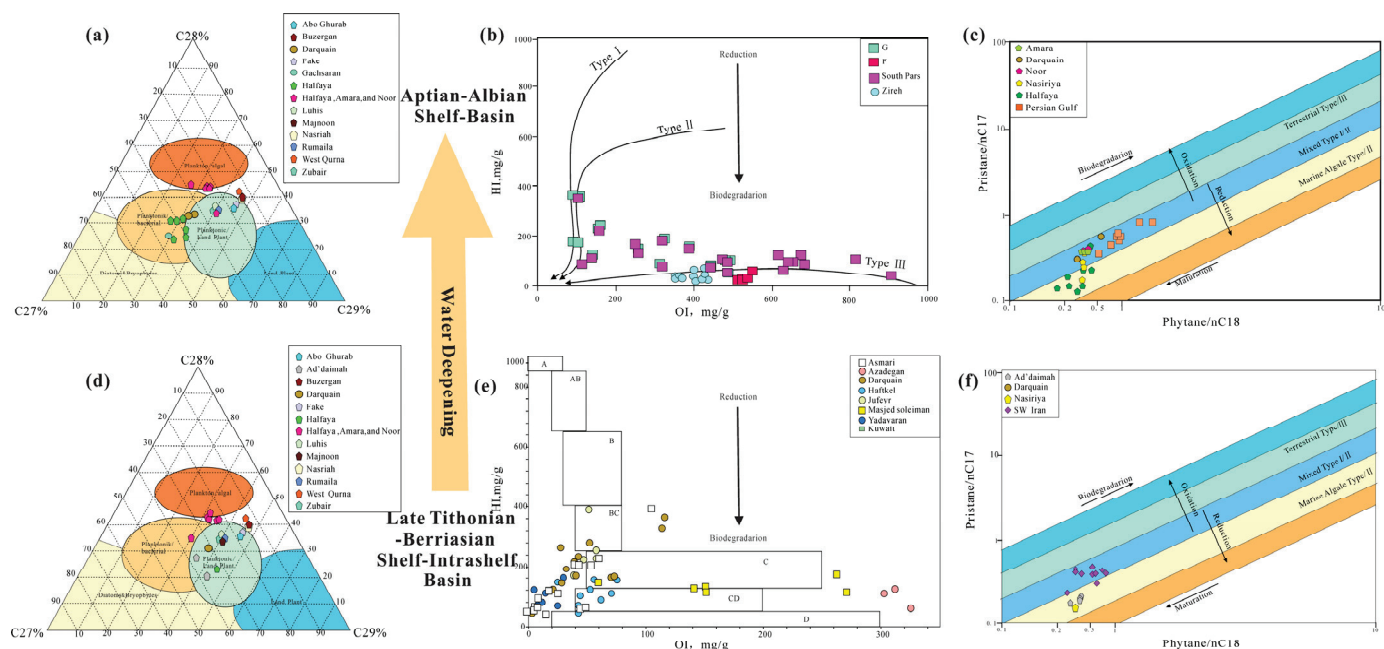


Figure 7. Depositional environments of the Late Tithonian–Berriasian and Aptian–Albian source rocks: (a) C₂₇–C₂₉ ternary diagram for Aptian–Albian source rocks; (b) HI–OI cross-plot for Aptian–Albian source rocks; (c) Pr/nC₁₇–Ph/nC₁₈ cross-plot for Aptian–Albian source rocks; (d) C₂₇–C₂₉ ternary diagram for the Late Tithonian–Berriasian source rocks; (e) HI–OI cross-plot for Late Tithonian–Berriasian source rocks; (f) Pr/nC₁₇–Ph/nC₁₈ cross-plot for the Late Tithonian–Berriasian source rocks. The water depth increased from the Late Tithonian–Berriasian stage to the Aptian–Albian stage.

4.4. Hydrocarbon Control Mechanisms

The hydrocarbon source rocks of the Late Tithonian–Berriasian stage were primarily distributed in intrashelf basins and on the shelf (Figure 8). The HI–Tmax cross-plot indicates that samples from the intrashelf basin facies exhibited a rich variety of organic matter types (Figure 8a), including Type I, II, and III, with the overall organic matter entering the oil window, predominantly in the mature to highly mature stage, and a small portion in the overmature stage. In contrast, samples from the shelf facies showed poorer organic matter types (Figure 8b), mainly Type II and III, with lower thermal evolution. Although they have entered the oil window, they were primarily in the mature stage.

The TOC–NA cross-plot reveals that samples from the intrashelf basin facies were generally of moderate-to-good quality (Figure 8c), with some being excellent. Samples from the shelf sedimentary facies ranged from poor to good (Figure 8d). In terms of organic matter type, maturity, and source rock quality, the intrashelf basin facies were superior to the shelf sedimentary facies, indicating that sedimentary environments significantly control the organic matter type, maturity, and quality of hydrocarbon source rocks.

The hydrocarbon source rocks of the Aptian–Albian stage were mainly distributed in areas with and without terrigenous input (Figure 8). The HI–Tmax cross-plot shows that samples from areas with terrigenous input had a diverse range of organic matter types (Figure 8f), including Type I, II, and III, with the organic matter generally entering the oil window, ranging from immature to mature stages. In contrast, samples from areas without terrigenous input were dominated by Type II or III organic matter, with thermal evolution primarily in the immature stage and a small portion reaching the mature stage (Figure 8e).

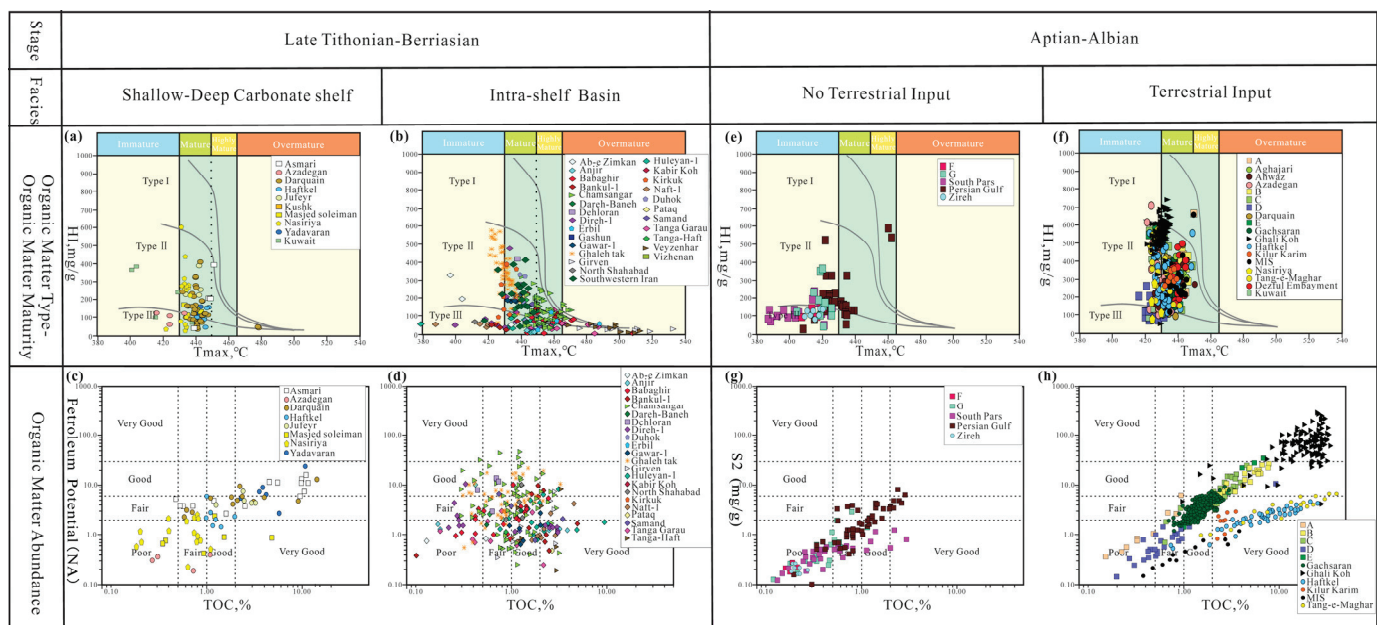


Figure 8. Hydrocarbon source rocks in Late Tithonian–Berriasian and Aptian–Albian facies. (a) HI-Tmax cross-plot, shelf facies (Late Tithonian–Berriasian); (b) HI-Tmax cross-plot, intrashelf basin facies (Late Tithonian–Berriasian); (c) NA-TOC cross-plot, shelf facies (Late Tithonian–Berriasian); (d) NA-TOC cross-plot, intrashelf basin facies (Late Tithonian–Berriasian); (e) HI-Tmax cross-plot, source rocks without terrigenous input (Aptian–Albian); (f) HI-Tmax cross-plot, source rocks with terrigenous input (Aptian–Albian); (g) S2-TOC cross-plot, source rocks without terrigenous input (Aptian–Albian); (h) S2-TOC cross-plot, source rocks with a terrigenous input (Aptian–Albian).

The S2-TOC cross-plot indicates that source rocks in terrigenous input areas were generally of moderate-to-very good quality, with a uniform distribution (Figure 8g). In contrast, source rocks in areas without terrigenous input ranged from poor to good, with a small portion being good (Figure 8h).

The HI-Tmax cross-plot further indicates that samples from the Aptian–Albian stage terrigenous input areas had richer organic matter types and higher thermal evolution compared to those from the Late Tithonian–Berriasian intrashelf basin facies. Additionally, the organic matter content in the Aptian–Albian stage source rocks was generally higher than that in the Late Tithonian–Berriasian stage, highlighting the significant contribution of terrigenous input to the quality and characteristics of hydrocarbon source rocks.

The hydrocarbon source rocks of the Late Tithonian–Berriasian and Aptian–Albian stages represent significant periods of source rock development in the Neo-Tethys Ocean. The formation of these source rocks primarily relied on favorable conditions in the shelf environment during extensive marine transgressions. Shelf areas are typically shallow marine environments with moderate water depths, providing excellent conditions for organic matter accumulation. During the formation of the Late Tithonian–Berriasian and Aptian–Albian source rocks, widespread marine transgressions created relatively stable marine conditions, facilitating the enrichment of organic matter. Additionally, the supply of nutrients from surface ocean waters promoted biological productivity, further enhancing the production of organic matter.

In the process of source rock formation, terrigenous input significantly improved the quality and distribution of the source rocks. In particular, under the conditions of upwelling seawater and continuous replenishment of sedimentary organic matter, both the quality and thickness of the source rocks were enhanced (Figure 9).

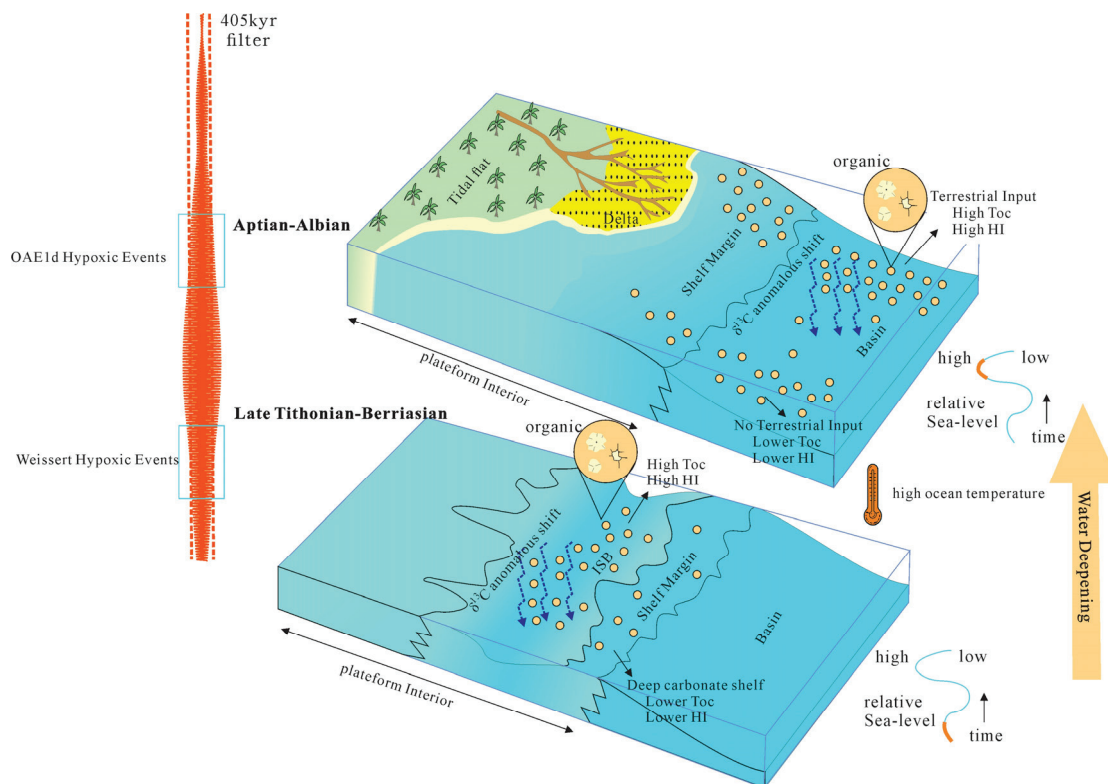


Figure 9. Sedimentary model of the Late Tithonian–Berriasian and Aptian–Albian stages.

5. Conclusions

Through time series analysis and high-resolution sequence stratigraphy, this study established the synchronicity of the two-phase source rocks (Late Tithonian–Berriasian and Aptian–Albian) in the northern Persian Gulf during the Early Cretaceous with global anoxic events (Weissert Event and OAE1d), demonstrating the significant contribution of widespread marine transgressions to the formation and organic matter enrichment of source rocks.

The research indicates that during the early stages of the Neo-Tethyan Ocean, the influence of residual topography led to the development of source rocks within the shelf–intraself basin facies association during the Middle–Late Jurassic to Early Cretaceous, showing a higher TOC, lower hydrogen index (HI), and higher maturity (Ro). As the Neo-Tethyan Ocean opened and water depths increased, the Aptian–Albian source rocks at the end of the Early Cretaceous primarily formed in the shelf–basin facies association, with the basin facies exhibiting higher organic matter abundance and maturity compared to the shelf facies.

Furthermore, this study reveals the following:

- (1) The organic matter content, type, and thermal evolution of the Late Tithonian–Berriasian source rocks are mainly controlled by sedimentary facies, with the intrashelf basin facies outperforming the shelf facies;
- (2) The characteristics of the Aptian–Albian source rocks are primarily regulated by terrestrial input, with the quality of basin source rocks in terrestrial input areas being significantly better than those in non-terrestrial input areas and contemporaneous shelf source rocks, highlighting the critical role of terrestrial input in improving source rock quality.

In summary, this study not only supplements the understanding of the depositional control mechanisms and organic matter evolution of the two-phase source rocks in the

northern Persian Gulf, but also provides systematic theoretical and practical guidance for regional hydrocarbon exploration. Future research could further explore the dynamic evolution of terrestrial and marine influences within different tectonic units through multi-scale geochemical and sedimentary modeling methods, aiming to provide more refined predictions for source rock accumulation in broader tectonic domains.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse13030576/s1>, Table S1: Hydrocarbon source rock quality evaluation indicators for the Late Tithonian–Berriasian and Aptian–Albian stages.

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Article

Development Characteristics of Natural Fractures in Metamorphic Basement Reservoirs and Their Impacts on Reservoir Performance: A Case Study from the Bozhong Depression, Bohai Sea Area, Eastern China

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Abstract: Archaean metamorphic basement reservoirs, characterized by the development of natural fractures, constitute the primary target for oil and gas exploration in the Bozhong Depression, Bohai Bay Basin, Eastern China. Based on analyses of geophysical image logs, cores, scanning electron microscopy (SEM), and laboratory measurements, tectonic fractures are identified as the dominant type of natural fracture. Their development is primarily controlled by lithology, weathering intensity, and faulting. Fractures preferentially develop in metamorphic rocks with low plastic mineral content and are positively correlated with weathering intensity. Fracture orientations are predominantly parallel or subparallel to fault strikes, while localized stress perturbations induced by faulting significantly increase fracture density. Open fractures, constituting more than 60% of the total reservoir porosity, serve as both primary storage spaces and dominant fluid flow conduits, fundamentally governing reservoir quality. Consequently, spatial heterogeneity in fracture distribution drives distinct vertical zonation within the reservoir. The lithological units are ranked by fracture development potential (in descending order): leptynite, migmatitic granite, gneiss, cataclasite, diorite-porphyrity, and diabase. Diabase represents the lower threshold for effective reservoir formation, whereas overlying lithologies may function as reservoirs under favorable conditions. The large-scale compressional orogeny during the Indosinian period marked the primary phase of tectonic fracture formation. Subsequent uplift and inversion during the Yanshanian period further modified and overlaid the Indosinian structures. These structures are characterized by strong strike-slip strain, resulting in a series of conjugate shear fractures. During the Himalayan period, preexisting fractures were primarily reactivated, significantly influencing fracture effectiveness. The development model of the fracture network system in the metamorphic basement reservoirs of the study area is determined by a coupling mechanism of dominant lithology and multi-phase fracturing. The spatial network reservoir system, under the control of multistage structure and weathering, is key to the formation of large-scale effective reservoirs in the metamorphic basement.

Keywords: natural fractures; fracture characteristics; controlling factors; metamorphic basement reservoir; fracture development pattern; Bozhong depression

1. Introduction

Basement reservoirs exhibit pronounced heterogeneity in their properties, with varied storage spaces and significant thicknesses of reservoir rock [1–3]. These reservoirs are widespread globally and are recognized as important sources of oil and gas [4,5]. The lithology of basement reservoirs is notably diverse, predominantly comprising metamorphic rocks, igneous rocks, sandstones, and carbonates [6,7]. Typically, basement reservoirs are classified into weathered crust reservoirs, located at structural elevations, and interior basement reservoirs. Basement reservoirs typically have undergone multiple phases of tectonic activity and diagenesis, leading to the development of natural fractures and secondary pores, making them highly heterogeneous [8–10].

The Bozhong Depression in the Bohai Bay Basin ranks among the most productive oil and gas regions in China. The extensive distribution of Archaean metamorphic basement reservoirs in deeper sections of the Bozhong Depression has greatly facilitated progress in oil and gas exploration [11,12]. Because primary pores are poorly developed in metamorphic rocks, natural fractures and associated secondary porosity are prevalent in these reservoirs. These natural fractures serve as primary storage spaces, playing a critical role in enhancing fluid migration and flow capacity within reservoirs [4,9]. Furthermore, fractures exert significant influence on reservoir fracturing reconstruction and the optimized design of petroleum engineering schemes [13–17]. Therefore, accurately characterizing the fracture system within these reservoirs is essential for the execution of fracturing and horizontal drilling operations, as well as for the strategic deployment of well patterns [18,19].

With advancements in oil and gas exploration and the development of metamorphic basement reservoirs, numerous studies have been conducted from both geological and engineering perspectives. Scholars have primarily investigated the formation mechanisms of these reservoirs and the key factors influencing their effectiveness. Furthermore, the studies that have been conducted on metamorphic basement reservoirs have explained mainly the strong heterogeneity and prominent vertical stratification of reservoirs [20–26]. Research has shown that metamorphic basement reservoirs are controlled to varying degrees by fracture distribution, and that their oil and gas bearing capacity and productivity strongly depend on natural fractures and later development plans [27–29]. However, while current research focuses on the use of geophysical and geological data to predict and characterize fractures in metamorphic basement reservoirs [30,31], the development characteristics of natural fractures, the controlling factors governing their formation, and their impact on reservoir quality remain incompletely understood. The fundamental causes of the distinct vertical zonation observed in metamorphic basement reservoirs also require further investigation [3]. Furthermore, the mechanisms underlying the genesis and development patterns of natural fractures in deep metamorphic basement reservoirs have not been thoroughly investigated [9].

This study investigates the metamorphic basement reservoirs in the Bozhong Depression by utilizing geophysical log data, cores, fluorescence scanning microscopy, SEM, and experimental data from 18 wells. It aims to elucidate the development characteristics of natural fractures in metamorphic basement reservoirs in the Bozhong Depression, and the main factors controlling the formation and development of fractures are discussed on the basis of geophysical log data. On the basis of the experimental data, the influence of open fractures on the storage space and fluid flow of metamorphic basement reservoirs is discussed, and the root cause of obvious vertical zonation of metamorphic basement reservoirs is discussed. Drawing on these results, spatial fracture network phylogenetic models are established for metamorphic basement reservoirs at different structural positions. These results can provide insights for the future exploration and exploitation of other metamorphic basement reservoirs.

2. Geological Setting

The Bohai Bay Basin, located in eastern China, has a rhombic shape and covers an area of approximately $20 \times 10^4 \text{ km}^2$, trending in a NW–SE direction (Figure 1A). It is a Mesozoic–Cenozoic superimposed basin that developed on the Paleozoic cratonic basement of North China through strike-slip and pull-apart tectonics [32–35]. The Bozhong Depression, the largest hydrocarbon-generating depression within the Bohai Bay Basin (Figure 1B), has developed a complex fault system since the Mesozoic. This system is characterized by early extensional faults, mid-phase strike-slip extensional faults, and late-stage strike-slip faults in localized areas. Multiple phases of fault activity control the distributions of various source rock sequences, influencing their thermal evolution. Additionally, the diverse trap types formed by faulting have provided favorable conditions for hydrocarbon accumulation, with faults acting as effective conduits for the vertical migration of hydrocarbons [36,37].

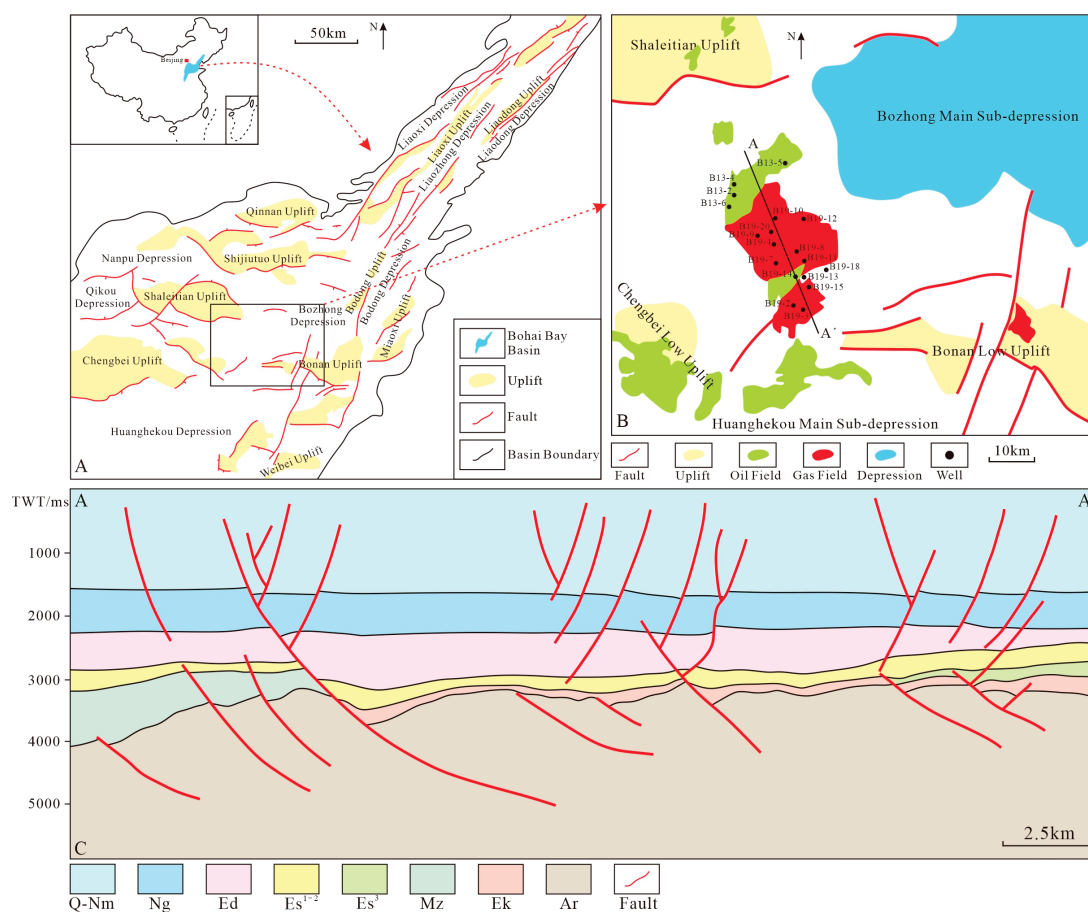


Figure 1. (A) The location of the Bozhong Depression in China (modified after [33]). (B) Locations of the study wells in the Bozhong Depression. (C) Typical geological section through the Bozhong Depression. The position of profile AA' is shown in (C).

The Bozhong Depression is underlain by basement rocks, with Paleozoic and Proterozoic strata entirely absent, and parts of the Mesozoic strata are also missing (Figure 2). The stratigraphic sequence encountered in boreholes, from top to bottom, includes the Quaternary Pingyuan Formation; the Neogene Minghuazhen and Guantao Formations; the Paleogene Dongying, Shahejie, and Kongdian Formations; Mesozoic strata; and the Archean metamorphic basement [38,39]. Owing to multiple phases of intense tectonic activity, the structural characteristics of the basement strata in the Bozhong Depression are highly complex, with different stratigraphic sequences in direct contact with each other

(Figure 1C). The Archean metamorphic rocks, which constitute the most extensive and oldest crystalline basement in the Bozhong Depression, constitute the primary focus of this study. These rocks are typically buried at depths greater than 4000 m, with exploratory wells revealing a maximum thickness exceeding 1300 m [40,41]. Hydrocarbons in the metamorphic basement reservoirs originate from three major source rocks: the third member of the Paleogene Shahejie Formation, the first member of the Shahejie Formation, and the third member of the Dongying Formation. The primary cap rocks for these reservoirs are the thick lacustrine mudstones of the Shahejie and Dongying Formations. This combination of source rocks, cap rocks, and reservoirs has ensured the preservation of oil and gas within metamorphic basement reservoirs over long geological periods, providing favorable conditions for hydrocarbon accumulation [42,43].

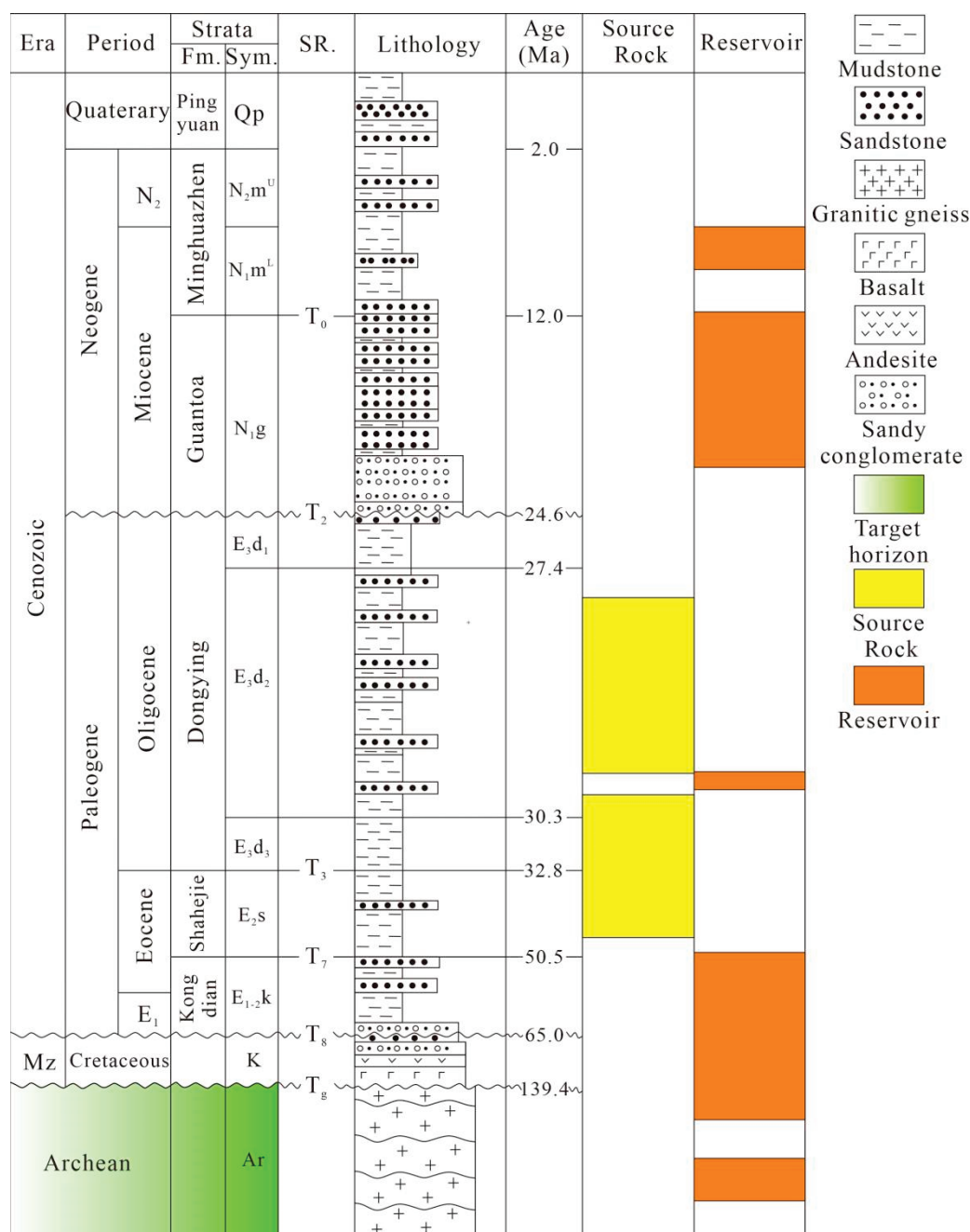


Figure 2. Stratigraphic framework of the Bozhong Depression, Bohai Bay Basin (after [42]). Light green indicates the main target layers.

Owing to multiple phases of intense compressional uplift, metamorphic basement reservoirs have experienced complex weathering processes, leading to the formation of weathered crust reservoirs at structural highs and interior basement reservoirs [44]. The storage spaces in these metamorphic basement reservoirs are diverse and primarily consist of natural fractures and secondary porosity. The physical properties of these reservoirs exhibit significant heterogeneity, with porosities ranging from 1% to 10% and an average porosity of 5.22%, while permeabilities range from 0.003 mD to 20.33 mD, with an average permeability of 0.37 mD [26].

3. Dataset and Methodology

The data and samples used in this study were collected from metamorphic basement reservoirs in the Bozhong Depression. These include cores, thin sections, SEM images, and geophysical log data from 18 vertical wells. A total of 109 thin sections (30 μm thick) were stained with blue or red resin dyes to enhance the visibility of fractures and pores [45]. Geophysical log data were employed to identify strong weathering fracture zones (SWFZs), weak weathering fracture zones (WWFZs), and basement zones (BZs). Additionally, this study utilized data from the Tianjin Branch of the China National Offshore Oil Corporation, along with relevant literature, to gather information on faults, stratigraphy, paleogeomorphology, and production data necessary for the research.

The characterization of natural fractures in metamorphic basement reservoirs is based on their orientation, dip angle, density, aperture, and filling conditions. Core observations and analyses were conducted at the core repository of the Tianjin Branch of the China National Offshore Oil Corporation. Notably, this method of studying fractures has certain limitations; for example, fracture information is only within the core scale because of the influence of core size, and some secondary fractures may be induced during the coring procedure. To distinguish between natural and induced fractures in the cores, the criteria established by Sangree (1969) [46] and Nelson (1985) [47] were applied.

Natural fractures identified in the image logs were processed and interpreted following established methods [48–50]. The results indicate that conductive fractures are typically filled with conductive mud or low-resistivity minerals, appearing as low-resistivity black sinusoidal curves in the image logs. In contrast, resistive fractures are generally filled with high-resistivity minerals, appearing as light-colored or white sinusoidal curves [45]. Fracture linear density was defined as the number of fractures observed per unit length in a specific direction, as observed in both cores and image logs. The aperture of fractures identified in the image logs was calculated via the formula proposed by Luthi and Souhaite (1990) [51]. Additionally, the porosities of the fractures in the image logs were calculated via the method proposed by Wang et al. (2022) [52].

At the Key Laboratory of Tectonics and Petroleum Resources, Ministry of Education, China University of Geosciences (Wuhan), natural fractures and pore characteristics in thin sections were identified and quantitatively measured using an OLYMPUS BH-2 polarizing microscope (Leica Company, Wetzlar, Germany) and a Philips XL30 SEM (Royal Philips, Eindhoven, The Netherlands) [53]. Additionally, fluorescence scanning of cores and thin sections was performed to analyze the hydrocarbon compounds present in natural fractures (Liu et al., 2020a) [25].

X-ray diffraction (XRD) analysis was conducted to determine the weight percentages of 43 metamorphic basement reservoir rock samples from 18 wells. The tests were performed using a D/max-2500 X-ray diffractometer (Rigaku Corporation, Tokyo, Japan). The test conditions included a tube voltage of 40 kV, a tube current of 200 mA, a temperature of 25 °C, and a humidity of 40%. The distribution of samples by lithology was as follows: leptynite (5), migmatitic granite (14), gneiss (9), cataclasite (6), diorite-porphyrite (5), and

diabase (4). The permeability and porosity of 51 metamorphic basement reservoir rock samples from 18 wells were measured using a helium porosimeter [54–57]. These standard core samples, each with a length of 5 cm (2 in) and a radius of 2.5 cm (1 in), were saturated with oil and dried prior to testing. The number of samples per lithology was as follows: leptynite (4), migmatitic granite (14), gneiss (18), cataclasite (6), diorite-porphyrity (5), and diabase (4).

4. Results

Since the beginning of the Cenozoic era, the metamorphic basement reservoirs in the Bozhong Depression have undergone prolonged and complex tectonic movements. Intense compression during the Indosinian period, in particular, provided the external mechanical conditions necessary for fracture formation. A significant number of fractures developed during the folding and uplift of these reservoirs. These fractures, which are closely associated with tectonic activity, are referred to as tectonic fractures [58] and constitute the primary type of natural fracture in the metamorphic basement reservoirs of the study area. Additionally, during the extensive burial and diagenetic evolution of the reservoirs, dissolution fractures formed due to the action of subsurface fluids associated with mineral dissolution. A systematic characterization of natural fractures in the metamorphic basement reservoirs of the Bozhong Depression was conducted through detailed observations and analyses of image logs, cores, thin sections, and scanning electron microscopy (SEM) data, in combination with the regional geological context.

4.1. Petrography

Analysis of core and image log data indicates that the lithologies of the metamorphic basement reservoirs in the Bohai Bay Basin primarily include gneiss, migmatitic granite, cataclasite, leptynite, and later intrusive dikes such as diorite-porphyrity and diabase. The X-ray diffraction (XRD) results (Table 1) indicate that the brittle mineral content varies among the different metamorphic rocks. In these rocks, brittle minerals are primarily composed of plagioclase, alkali feldspar, and quartz, whereas plastic minerals primarily consist of amphibole, biotite, and pyroxene. In the metamorphic basement of the Bozhong Depression, leptynite contains more than 90% brittle minerals and only a very small proportion of plastic minerals. Migmatitic granite and gneiss also exhibit high brittle mineral contents, exceeding 80%, with the remainder composed of plastic minerals. In contrast, later intrusive dikes, such as diorite-porphyrity and diabase, contain lower brittle mineral contents (less than 75%) and relatively higher proportions of plastic minerals.

Table 1. Semi-quantitative amounts of minerals in the different rock units in the metamorphic basement reservoir of the Bozhong Depression, Bohai Bay Basin (average weight percent, %).

Petrology	Quartz (wt.%)	Alkaline Feldspar (wt.%)	Plagioclase (wt.%)	Biotite (wt.%)	Amphibole (wt.%)	Pyroxene (wt.%)	Others (wt.%)
Leptynite	49.6	22.3	21.5	0.9	1.2	0	4.5
Migmatitic Granite	31.3	28.3	30.5	4.3	3.8	0	1.8
Gneiss	9.3	39.6	31.8	7.9	8.3	0	3.1
Cataclasite	11.3	32.2	34.5	9.3	9.5	0	3.2
Diorite-Porphyrity	8.1	20.3	45.1	10.1	14.3	0	2.1
Diabase	7.5	19.5	32.3	2.3	0.8	21.2	16.4

The permeability and porosity test results of rock samples from metamorphic basement reservoirs show that rocks rich in brittle minerals possess better reservoir properties than those rich in plastic minerals. Leptynite exhibits the most favorable physical properties,

with an average porosity of 4.6% and an average permeability of $0.578 \times 10^{-3} \mu\text{m}^2$, followed by migmatitic granite, which has an average porosity of 3.2% and an average permeability of $0.142 \times 10^{-3} \mu\text{m}^2$. In contrast, late intrusive diorite-porphyrite and diabase exhibit the poorest physical properties, with average porosities of 2.1% and 1.7%, respectively, and average permeabilities of $0.041 \times 10^{-3} \mu\text{m}^2$ and $0.039 \times 10^{-3} \mu\text{m}^2$, respectively (Table 2).

Table 2. Porosity and permeability of rocks with different lithologies in metamorphic basement reservoirs of the Bozhong depression, Bohai Bay Basin.

Petrology	Number of Samples	Porosity (%)			Permeability ($\times 10^{-3} \mu\text{m}^2$)		
		Minimum	Maximum	Average	Minimum	Maximum	Average
Leptynite	4	2.4	8.8	4.6	0.164	0.881	0.578
Migmatitic Granite	14	0.7	6.1	3.2	0.053	0.728	0.142
Gneiss	18	1.2	8.7	2.8	0.022	0.259	0.068
Cataclasite	6	0.7	6.2	2.6	0.021	0.221	0.067
Diorite-Porphyrite	5	0.8	5.8	2.1	0.024	0.046	0.041
Diabase	4	1.3	2.0	1.7	0.019	0.063	0.039

4.2. Characteristics of Natural Fractures by Image Logs

Image logs reveal that tectonic fractures in the metamorphic basement reservoirs of the study area are predominantly medium-angle fractures, with low-angle and high-angle fractures comprising a relatively small proportion. High-angle fractures (dips $> 75^\circ$) account for 5.6% of all fractures, while low-angle fractures (dips $< 25^\circ$) represent 12.5%. Medium-angle fractures (dipping between 25° and 75°) constitute 81.9% of all the fractures. The aperture of tectonic fractures varies significantly with dip angle: low-angle fractures typically have apertures of less than $50 \mu\text{m}$, medium-angle fractures generally range from 50 – $100 \mu\text{m}$, and high-angle fractures often exceed $100 \mu\text{m}$. The fractures are primarily oriented in nearly E–W, NE–SW, NW–SE, and ENE–WSW directions. Among these fractures, those oriented ENE–SW and NW–SE are the most prevalent, while those oriented NE–SW and nearly E–W are less common (Figure 3). In the image logs, most tectonic fractures are unfilled, with filled fractures comprising only 38% of the total fractures (Figure 4). Dissolution fractures, formed by the dissolution of early tectonic fractures, are also observed in the image logs (Figure 5).

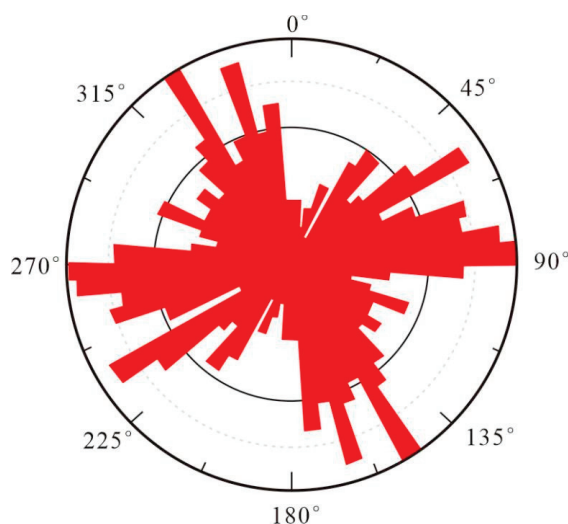


Figure 3. Rose diagrams showing the dominant orientations of tectonic fractures in metamorphic rocks of the Bozhong Depression, Bohai Bay Basin, identified based on image logs (N = 6066).

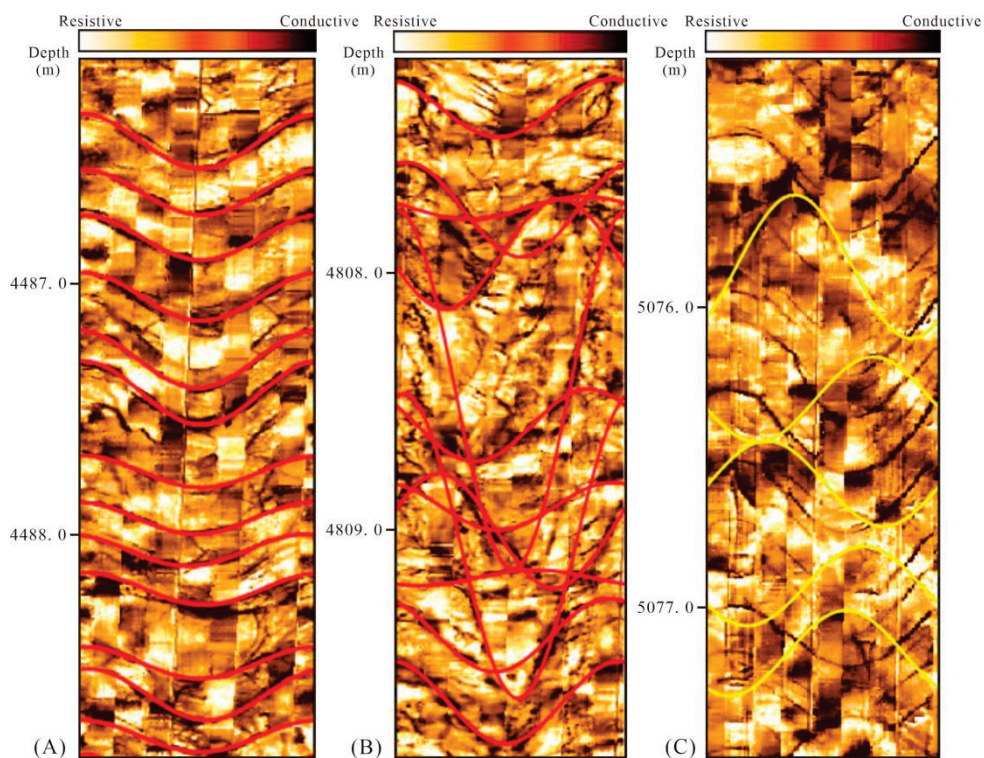


Figure 4. Tectonic fracture characteristics observed in image logs of metamorphic rocks from the Bozhong Depression, Bohai Bay Basin. (A) Unfilled, grouped tectonic fractures with similar occurrence from Well B13-4. (B) Unfilled mesh tectonic fractures from Well B13-4. (C) Filled tectonic fractures from Well B13-2. (The red lines represent the unfilled tectonic fractures; the yellow lines represent the filled tectonic fractures).

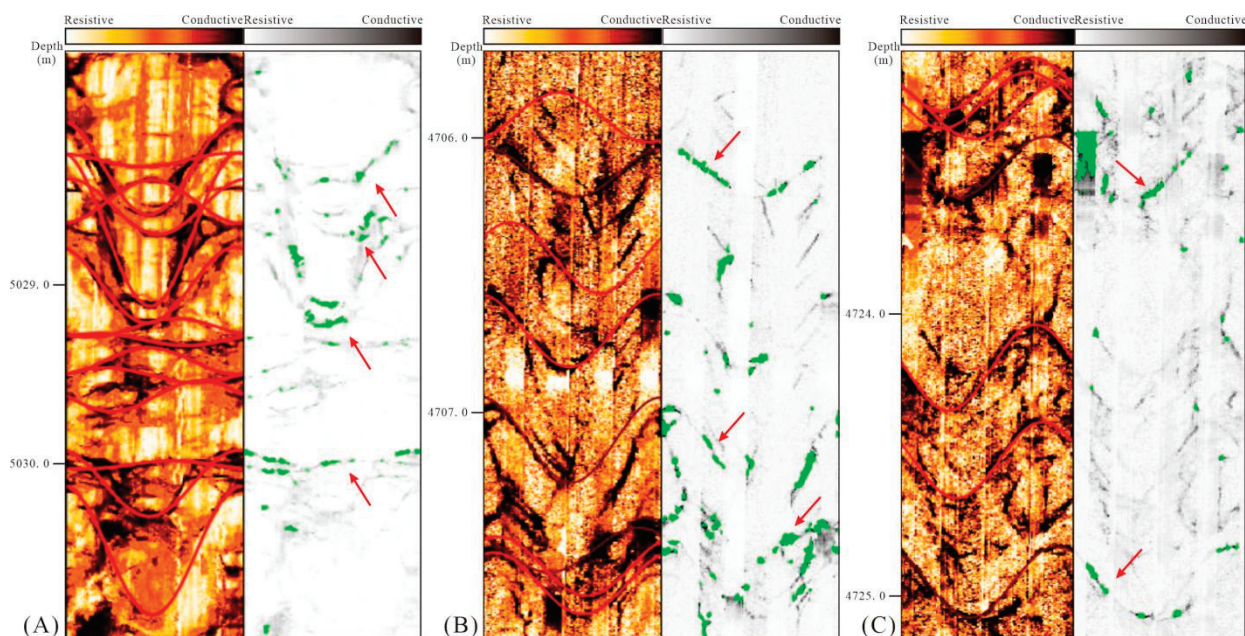


Figure 5. Dissolution fracture characteristics observed in image logs of metamorphic rocks from the Bozhong Depression, Bohai Bay Basin. (A) Dissolution fractures from Well B19-9. (B) Dissolution fractures from Well B19-8. (C) Dissolution fractures from Well B19-8. (Green indicates that the fractures have been dissolutioned).

The image logs reveal significant variations in the degree of tectonic fracture development among the various rock types within the metamorphic basement reservoirs of

the Bozhong Depression. Leptynite exhibits the highest average linear density of tectonic fractures (1.52 m^{-1}), followed by migmatitic granite (1.12 m^{-1}), granitic gneiss (1.10 m^{-1}), and cataclasite (1.06 m^{-1}). In contrast, the diorite-porphyrite and diabase samples exhibit lower average linear densities of tectonic fractures, at 0.65 m^{-1} and 0.58 m^{-1} , respectively.

4.3. Characteristics of Natural Fractures by Cores

Core inspections reveal that the surfaces of tectonic fractures are typically uneven (Figure 6A,C,D) and exhibit irregular development (Figure 6B). Fractures with different orientations intersect or terminate against one another (Figure 6D), forming a network fracture system through mutual crosscutting (Figure 6B). The lengths of tectonic fractures are generally less than 30 cm, with most fractures ranging between 5 and 20 cm. Statistical analysis indicates that the distribution of tectonic fractures is highly heterogeneous, with average fracture linear densities ranging from $1\text{--}6 \text{ m}^{-1}$ and maximum values reaching up to 12 m^{-1} .



Figure 6. Tectonic fracture characteristics in cores of metamorphic rocks from the Bozhong depression, Bohai Bay Basin. (A) High-angle fractures from Well B19-7 at a depth of 4683.21 m; fracture surfaces are uneven. (B) Fractures from Well B19-14 at a depth of 4362.46 cm; tectonic fractures intersect to form a network of fracture systems. (C) High-angle fractures from Well B19-7 at a depth of 4625.56 m; fracture surfaces are uneven. (D) Tectonic fractures from Well B19-7 at a depth of 4682.22 m; later fractures in Group B terminate earlier fractures in Group A.

4.4. Characteristics of Natural Fractures by Thin Sections and SEM Images

The development of different types of microfractures in metamorphic basement reservoirs varies significantly. Statistical analysis indicates that the average surface density of intragranular fractures is 3.7 mm mm^{-2} , whereas the average surface density of intergranular fractures is lower, at only 0.61 mm mm^{-2} . The aperture of intragranular fractures is generally small, typically less than $10 \mu\text{m}$, whereas the aperture of intergranular fractures is larger, ranging between 15 and $30 \mu\text{m}$. In terms of fracture filling, 43% of the fractures are filled primarily with clay minerals, followed by carbonate fillings (Figure 7A,B). Fractures filled with quartz and bitumen are less common (Figure 7C). Additionally, some early-filled fractures were reopened under the influence of subsequent tectonic movements, with carbonate cement precipitating to form bright calcite filling layers (Figure 7D).

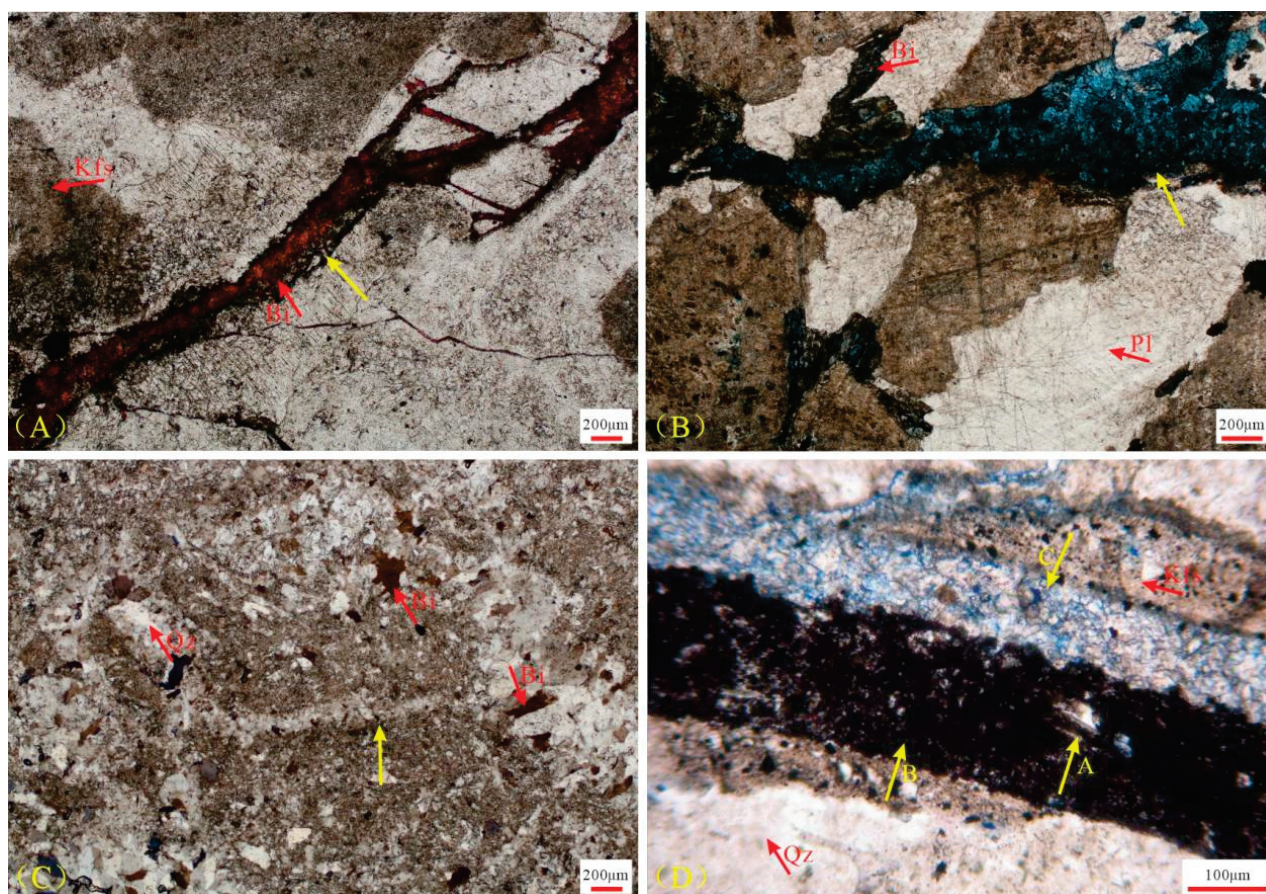


Figure 7. Filling characteristics of tectonic fractures in thin sections of metamorphic rocks from the Bozhong Depression, Bohai Bay Basin. (A) Calcite-filled fractures in migmatitic granite from Well B19-9 at a depth of 5265 m. (B) Dolomite-filled fractures in gneiss from Well B19-2 at a depth of 4225 m. (C) Quartz-filled fractures in cataclasite from Well B19-9 at a depth of 5139 m. (D) Three-stage fracture filling in gneiss from Well B19-12 at a depth of 3878 m. Arrows labeled A, B, and C indicate: A, the first stage of filling with microcrystalline felsic material; B, the second stage of filling with limonite; and C, the third stage of filling with iron dolomite after the early cracks reopened. Qz: quartz, Bi: biotite, Pl: plagioclase, Kfs: K-feldspar.

Owing to prolonged weathering and leaching, metamorphic basement reservoirs commonly exhibit dissolution fractures formed by the modification of early fractures through dissolution processes [59]. Dissolution fractures are typically curved, branched, or network-like in distribution, and their edges are serrated, with dissolution traces, and the tectonic fracture surface is relatively flat. Dissolution holes often develop around dissolution fractures, such as “beaded” pores distributed along fractures. In addition, local

dissolution fractures often widen, or dissolution holes can form. When early fractures are altered by subsequent fluid activity, their apertures increase, fracture surfaces become rougher, and their shapes become more irregular (Figure 8A). Additionally, as atmospheric freshwater percolates downward along tectonic fractures, the unstable minerals in the fracture fillings are either partially or completely dissolved, rendering previously filled fractures effective once again [60,61] (Figure 8B). However, owing to the lithological and structural characteristics of metamorphic basement reservoirs, dissolution fractures are less common than tectonic fractures and have relatively less significance in the processes of hydrocarbon migration and accumulation.

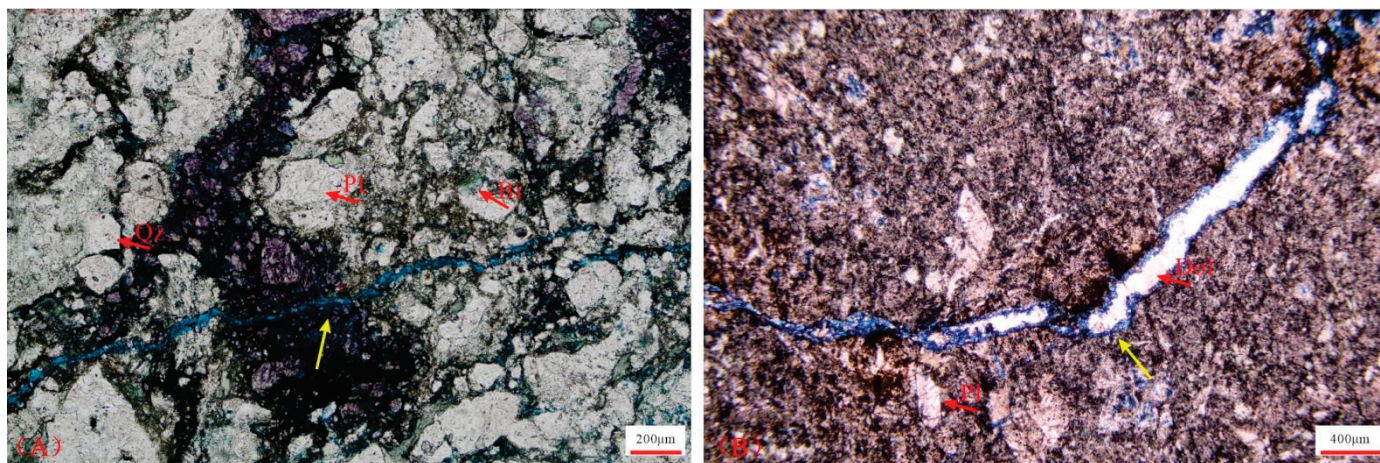


Figure 8. Dissolution fracture characteristics in thin sections of metamorphic rocks from the Bozhong Depression, Bohai Bay Basin. (A) Dissolution fractures in diorite-porphyrity from Well B19-13 at a depth of 4490 m; early tectonic fractures have been transformed by dissolution. (B) Dissolution fractures in diorite-porphyrity from B19-8 at a depth of 4731 m; partial dissolution of dolomite filling has reactivated the fracture. Qz: quartz, Pl: plagioclase, Dol: dolomite, Bi: biotite.

SEM images reveal the development of microfractures in metamorphic basement reservoirs. On the basis of the relationship between fractures and mineral grains, microfractures can be categorized into two types: (1) intergranular fractures and (2) intragranular fractures. Intergranular fractures occur along the edges of grains or cut directly through larger mineral crystals [62] (Figure 9A). These fractures can be further divided into two types on the basis of their development characteristics: the first type develops along the edges of mineral crystals, with varying lengths and curved, irregular fracture surfaces; the second type cuts directly through larger mineral crystals such as quartz and feldspar, sometimes appearing in clusters and extending over longer distances. Intragranular fractures typically occur within mineral crystals such as quartz, mica, and feldspar, and their size is constrained by the grain size. Cleavage fractures, which are found in feldspar and mica, and crack fractures, which are found in quartz, represent the primary types of intragranular fractures (Figure 9B). Generally, one set of cleavage fractures forms in mica (Figure 9C), whereas two sets of parallel cleavage fractures develop in feldspar (Figure 9D). Cleavage fractures are relatively uniformly distributed and straight, whereas crack fractures are irregularly distributed, with curved fracture surfaces.

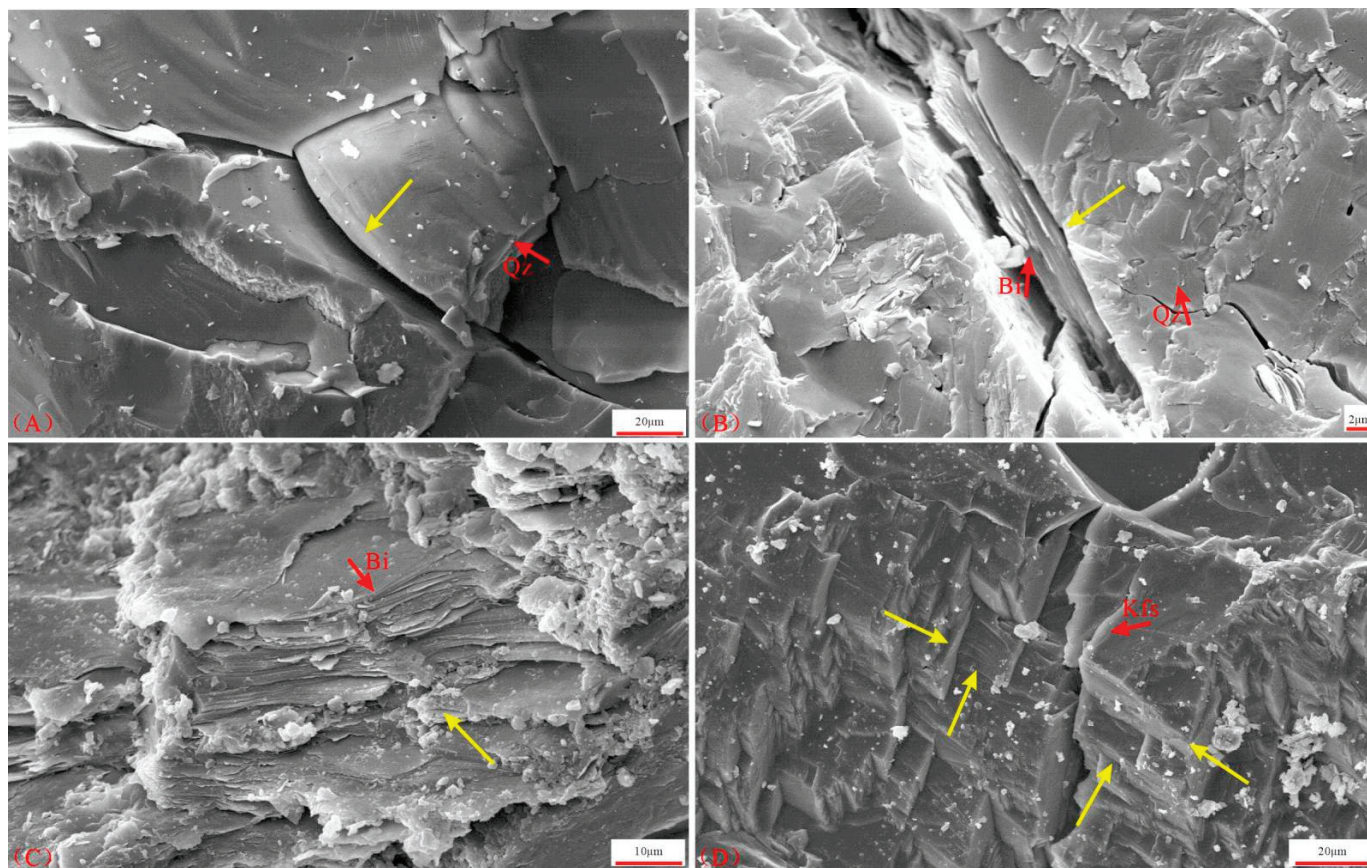


Figure 9. Tectonic fracture characteristics observed in SEM images of metamorphic rocks from the Bozhong Depression, Bohai Bay Basin. (A) Intergranular fracture development in quartz particles in gneiss from Well B19-10 at a depth of 4478 m. (B) Crack fractures within quartz particles in gneiss from Well B19-15 at a depth of 5038 m. (C) Regularly developed mica cleavage fractures in migmatitic granite from Well B19-7 at a depth of 4757 m. (D) Two sets of regularly developed cleavage fractures in potassium feldspar in migmatitic granite from Well B19-7 at a depth of 4753 m. Qz: quartz, Kfs: K-feldspars, Bi: biotite.

5. Discussion

5.1. Factors Controlling Fracture Development

(1) Lithotypes

Lithology is a fundamental factor influencing fracture development. The average linear density of fractures in different rock types is positively correlated with brittle mineral content and negatively correlated with plastic mineral content (Table 1), whereas the plastic mineral content is relatively high. Rocks with lower plastic mineral content exhibit a lower ratio of cohesion modulus to elastic modulus, resulting in greater brittleness [63,64]. Under tectonic stress, these rocks are more prone to fracturing, leading to increased fracture development. Therefore, variations in mineral composition significantly impact tectonic fracture development in metamorphic basement reservoirs.

Core and thin section observations reveal that as the content of plastic minerals in rock increases, fractures are more likely to be filled with minerals, thereby reducing fracture effectiveness. In diorite-porphyrite and diabase, more than 83% of the fractures are filled. In contrast, the proportion of filled fractures is only 26% in migmatitic granite and 35% in gneiss, with almost no filled fractures in leptynite, resulting in greater fracture effectiveness. Additionally, rocks with a high content of brittle minerals exhibit a high degree of compositional and structural heterogeneity and contain minerals of various sizes,

compositions, and shapes. The differential deformation rates of these grains under stress lead to force transmission, and deformation leads to an uneven stress field distribution within the rock, promoting fracture development [65,66].

(2) Faulting

Faults influence the local stress distribution and thereby control fracture development. They are critical factors in controlling the heterogeneity of fracture development [67]. Rose diagrams of fracture orientations from 12 wells in the study area (Figure 10) reveal that fracture orientations are parallel or nearly parallel to the adjacent faults, indicating their significant influence on fracture development. During the early Indosinian period, nearly N–S compressive stress caused fractures and faults to align parallelly. The predominant NE–E orientation of faults and fractures in the study area suggests that intense compressive stress during this period was instrumental in fracture development [9]. Notably, the rose diagrams of fracture orientations in wells B13-2, B13-6, B19-8, and B19-14 reveal a significant number of N–E-oriented fractures, which align with the adjacent N–E-oriented faults, indicating that local stresses from these faults during the Yanshanian period also played a significant role. Additionally, fracture development is greater at fault intersections. For example, Well B19-8, located at a fault intersection, exhibited a high fracture linear density of 1.6 m^{-1} . Furthermore, Well B19-8 features highly developed cataclastic zones with a distinct directionality, resulting from the combined effects of shear stress and tensile stress [65].

(3) Weathering

The long geological evolution of the Bozhong Depression led to extended periods of weathering and erosion in the basement metamorphic rocks. Feldspar minerals, which are less resistant to weathering, underwent significant alteration, increasing rock fragmentation. Following physical weathering, chemical leaching and dissolution further modified the basement metamorphic rocks, influencing fracture formation and development.

On the basis of weathering intensity, the metamorphic basement reservoirs in the Bozhong Depression are vertically divided into a strong weathering fracture zone (SWFZ), a weak weathering fracture zone (WWFZ), and a basement zone (BZ). Image logs and core data from Well B19-15 (Figure 11) indicate that in the SWFZ, fractures intersect to form a network, with multiple dissolution pores and fractures observed. In the WWFZ, fracture development is lower than in the SWFZ, with fractures often occurring individually. In the BZ, image logs and core data show that pores and fractures are poorly developed. Overall, the degree of fracture development decreases as the weathering intensity decreases.

Table 3 presents the fracture linear density and fracture porosity characteristics across the strong and weak weathering fracture zones and the basement zone in the Bozhong Depression. As the weathering intensity decreases, which reduces the mechanical properties of reservoir rocks, the linear fracture density decreases progressively from the strong to the weak weathering zones and into the basement, indicating reduced fracture development. However, in some wells, the basement zone exhibits higher fracture porosity than the weathered zones due to clay layer formation from intense weathering [9,68]. Continued weathering intensifies mineral dissolution, causing increased precipitation of minerals such as clay and calcite, which can clog pores and fractures. This extensive fracture and pore filling explains why some wells have greater fracture porosity in the basement zone than in the weathering zones.

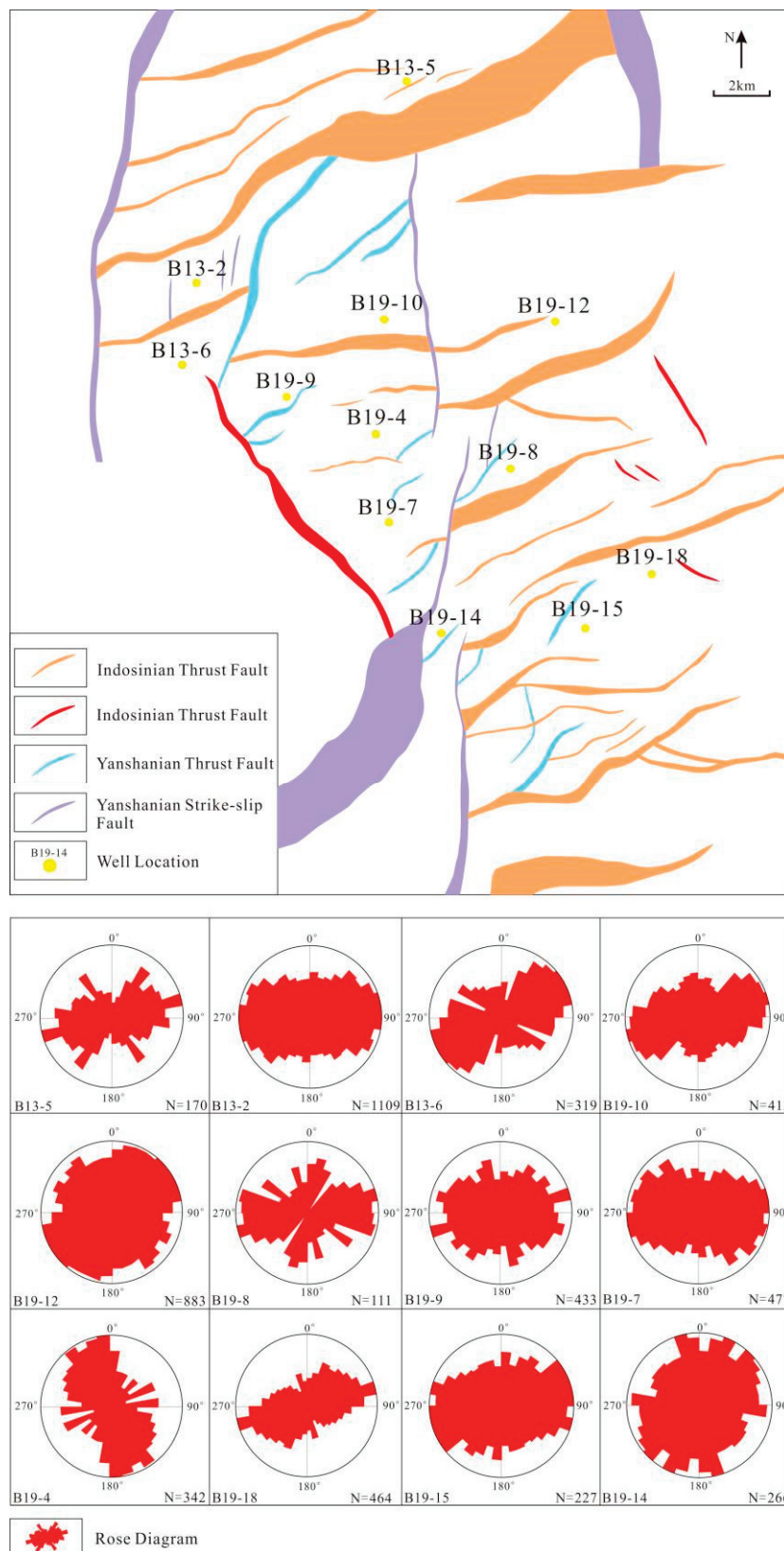


Figure 10. Major fault and tectonic fracture orientations of metamorphic basement reservoirs in the Bozhong Depression, Bohai Bay Basin. (Tianjin Branch of China National Offshore Oil Corporation).

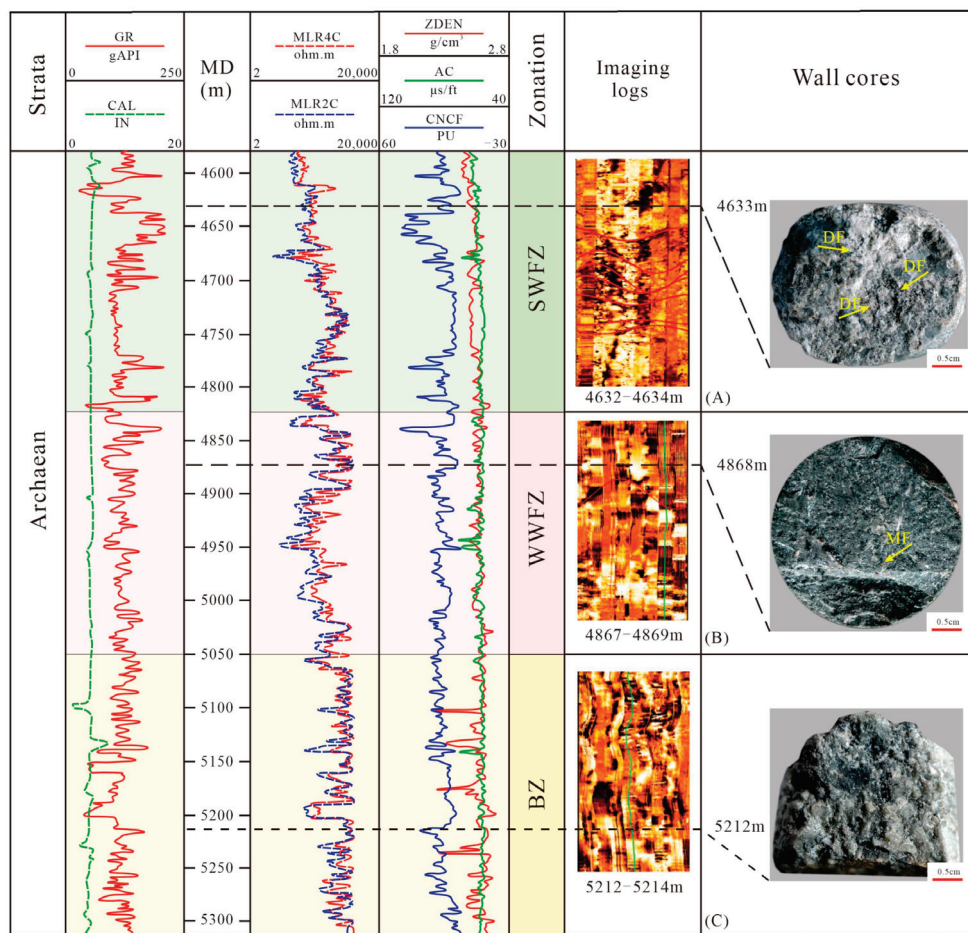


Figure 11. Vertical stratification of metamorphic rock reservoirs in Well B19-15, Bozhong Depression, Bohai Bay Basin. The degree of fracture development gradually decreases from the strong weathering fracture zone (SWFZ), through the weak weathering fracture zone (WWFZ), to the basement zone (BZ). DF: dissolution fracture; MF: microfracture. (A) Cores at a depth of 4633 m; (B) Cores at a depth of 4868 m; (C) Cores at a depth of 5212 m.

Table 3. Characteristics of the fracture density and aperture in the strong weathering fracture zone (SWFZ), weak weathering fracture zone (WWFZ), and basement zone (BZ).

Well	Fracture Density of Strong Weathering Fracture Zone (m^{-1})	Fracture Density of Weak Weathering Fracture Zone (m^{-1})	Fracture Density of Basement Zone (m^{-1})	Fracture Porosity of Strong Weathering Fracture Zone (%)	Fracture Porosity of Weak Weathering Fracture Zone (%)	Fracture Porosity of Basement Zone (%)
B19-2	0.52	0.45	0.39	4.0	3.8	4.2
B19-7	1.21	1.13	1.02	3.2	2.8	2.7
B19-10	0.91	0.62	0.45	4.3	3.8	3.4
B19-11	0.28	0.11	0.04	3.2	3.1	3.6
B19-12	1.57	1.23	1.16	3.5	2.9	2.6
B19-14	2.01	1.63	0.75	5.8	5.4	5.0
B19-15	0.74	0.52	0.41	3.0	2.7	3.3

The duration and intensity of weathering and leaching in metamorphic basement reservoirs vary on the basis of paleogeomorphology, with higher paleogeomorphic positions typically experiencing longer exposures. Paleogeomorphic elevation, often indicated by the thickness of the overlying sedimentary layers, generally correlates positively with

this thickness. Statistical analysis revealed a negative correlation between the thickness of these layers and the average fracture linear density and aperture in the strong weathering zone (Figure 12), suggesting greater fracture development at higher paleogeomorphic positions. However, the correlation is not strong, indicating that fracture development in metamorphic basement reservoirs is influenced by multiple factors beyond paleogeomorphology.

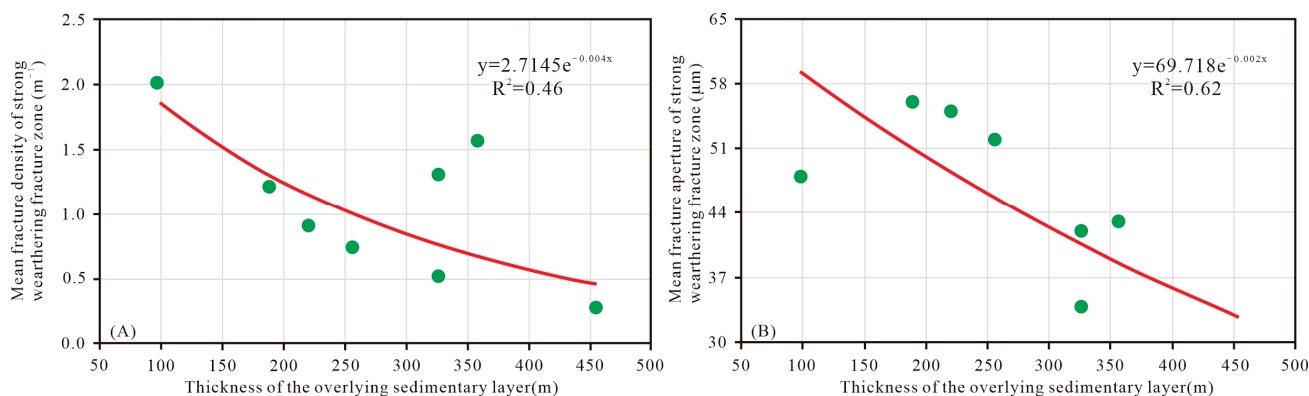


Figure 12. (A) Relationship between the average fracture linear density of the strong weathering fracture zone (SWFZ) and the thickness of the overlying sedimentary layer. (B) Relationship between the average fracture aperture of the SWFZ and the thickness of the overlying sedimentary layer.

5.2. Vertical Stratification of Reservoirs

The metamorphic basement reservoirs in the Bozhong Depression show significant vertical heterogeneity, characterized by stratified hydrocarbon accumulation. This heterogeneity arises from variations in fracture development across rock types, leading to differences in porosity, permeability, and reservoir quality. High-quality reservoirs form in rocks with better physical properties and more fractures, whereas rocks with lower fracture development act as interlayers. These interlayers create multiple distinct pressure systems, contributing to the strong vertical heterogeneity observed in these reservoirs.

Core physical property tests revealed that rocks rich in brittle minerals exhibit better reservoir properties than those rich in plastic minerals. Statistical analysis revealed a positive correlation between the physical properties of different lithologies and the degree of tectonic fracture development across different lithologies (Figure 13, Tables 1 and 3). Fractures are crucial for providing storage space and migration pathways for hydrocarbons, making them essential to effective reservoir formation. Thus, variations in fracture development are the primary cause of vertical stratification in metamorphic basement reservoirs.

In the Bozhong Depression, the lithologies of metamorphic basement reservoirs, ranked by fracture development from highest to lowest, are leptynite, migmatitic granite, gneiss, cataclasite, diorite-porphyrite, and diabase. As the plastic mineral content (e.g., biotite and amphibole) increases and the brittle mineral content (e.g., quartz and plagioclase) decreases, the likelihood of forming effective reservoirs diminishes under comparable geological conditions. Production data indicate that lithologies preceding diorite-porphyrite in this sequence generally bear hydrocarbons and serve as main reservoir rocks, with well-developed, unmineralized fractures. In contrast, diorite-porphyrite and diabase exhibit poorer physical properties but possess better sealing abilities and often act as interlayers within reservoirs.

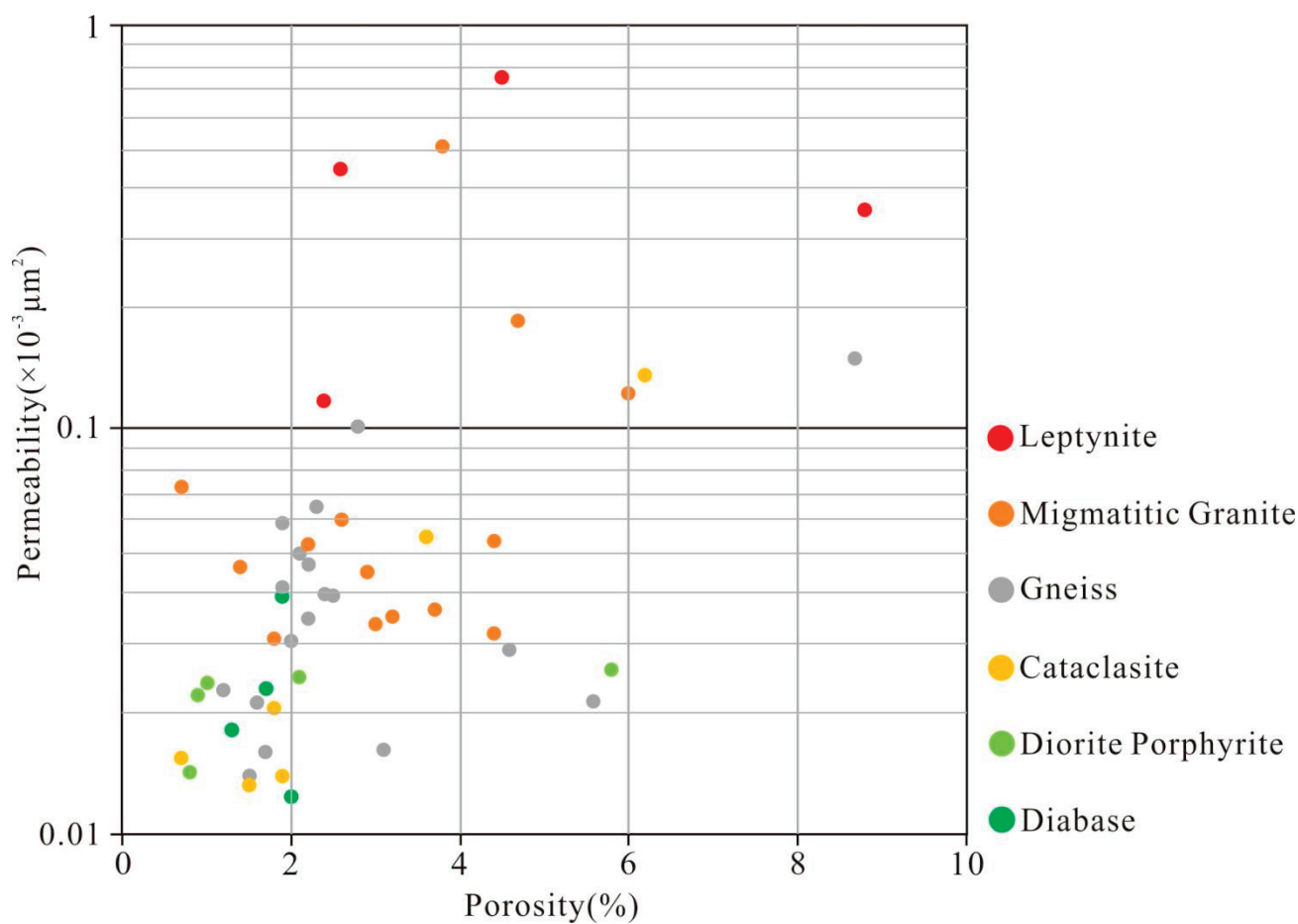


Figure 13. Relationship between permeability and porosity based on physical property analysis of basement reservoirs in the Bozhong Depression, Bohai Bay Basin (N = 51).

On the basis of well test data, metamorphic basement reservoirs in the Bohai Bay Basin are classified into three levels: (1) Level I, with production above $1 \times 10^4 \text{ m}^3/\text{d}$; (2) Level II, with production between 0.1×10^4 and $1 \times 10^4 \text{ m}^3/\text{d}$; and (3) Level III, with production below $0.1 \times 10^4 \text{ m}^3/\text{d}$, often indicating dry layers or interlayers. In Well B19-15, leptynite is a Level I reservoir due to its high quality and better fracture development, while gneiss is classified Level II or III (Figure 14A). In Well B19-18, gneiss ranks as Level I and II, whereas diorite-porphyrite is Level III due to poorer fracture development (Figure 14B). In Well B19-14, diorite-porphyrite is classified as Level II and is confirmed as hydrocarbon-bearing (Figure 14C). Consistently, diabase in multiple wells (e.g., Well B19-20) is classified as Level III, functioning as an inner interlayer rather than an effective reservoir (Figure 14D). These examples indicate that lithologies preceding diabase may serve as reservoir rocks or interlayers, whereas diabase functions only as an interlayer.

In metamorphic basement reservoirs, the potential for rocks to become reservoir rocks is limited by their position in the lithological sequence. In the Bozhong Depression, diabase marks the lower limit. Lithologies preceding it can become reservoir rocks under suitable geological conditions, while diabase and those following serve as interlayers. However, the formation of reservoir rocks still depends on the extent of fracture development. This arrangement of reservoirs and interlayers establishes a favorable geological framework for hydrocarbon accumulation.

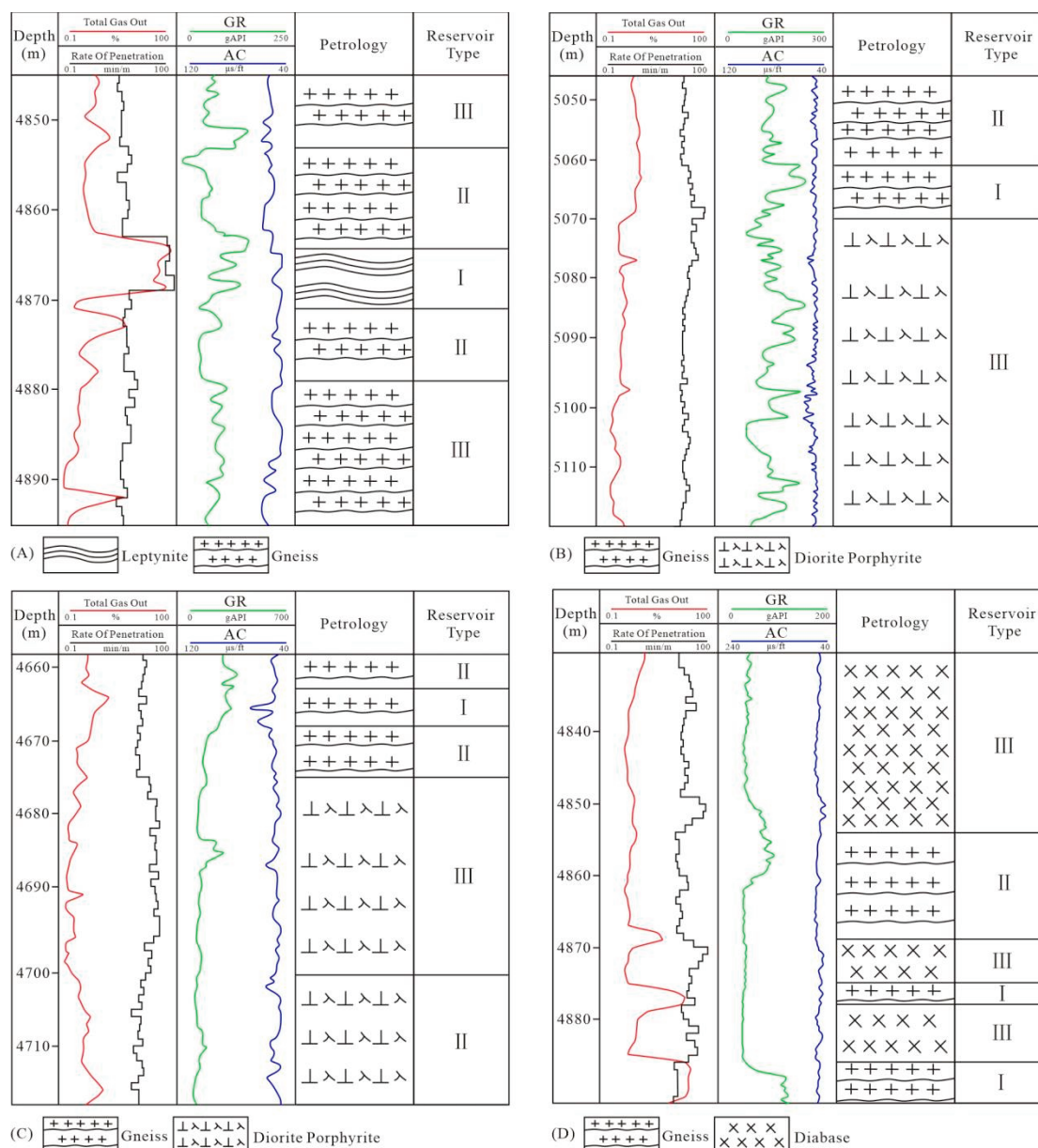


Figure 14. Metamorphic basement reservoir types in the Bozhong Depression, Bohai Bay Basin. (A) Well B19-15: Leptynite is classified as a Level I reservoir, and gneiss as Level II and III reservoirs. (B) Well B19-18: Gneiss is classified as Level I and II reservoirs, and diorite-porphyrite as a Level III reservoir. (C) Well B19-14: Gneiss is classified as Level I and II reservoirs, and diorite-porphyrite as Level II and III reservoirs. (D) Well B19-20: Gneiss is classified as Level I and II reservoirs, and diabase as a Level III reservoir.

5.3. Fracture Patterns in Metamorphic Rocks

During the early Indosinian period, the metamorphic basement reservoirs of the Bozhong Depression in the Bohai Bay Basin underwent intense NNW–SSE compressional orogeny. According to the Coulomb fracture criterion, an increase in the maximum principal stress expands the Mohr stress circle, causing it to intersect with the fracture envelope and resulting in rock fracturing. This process primarily produced medium- to low-angle shear fractures trending NEE–WSW, along with high-angle shear, high-angle longitudinal extension, and transverse extension fractures (Figure 15A).

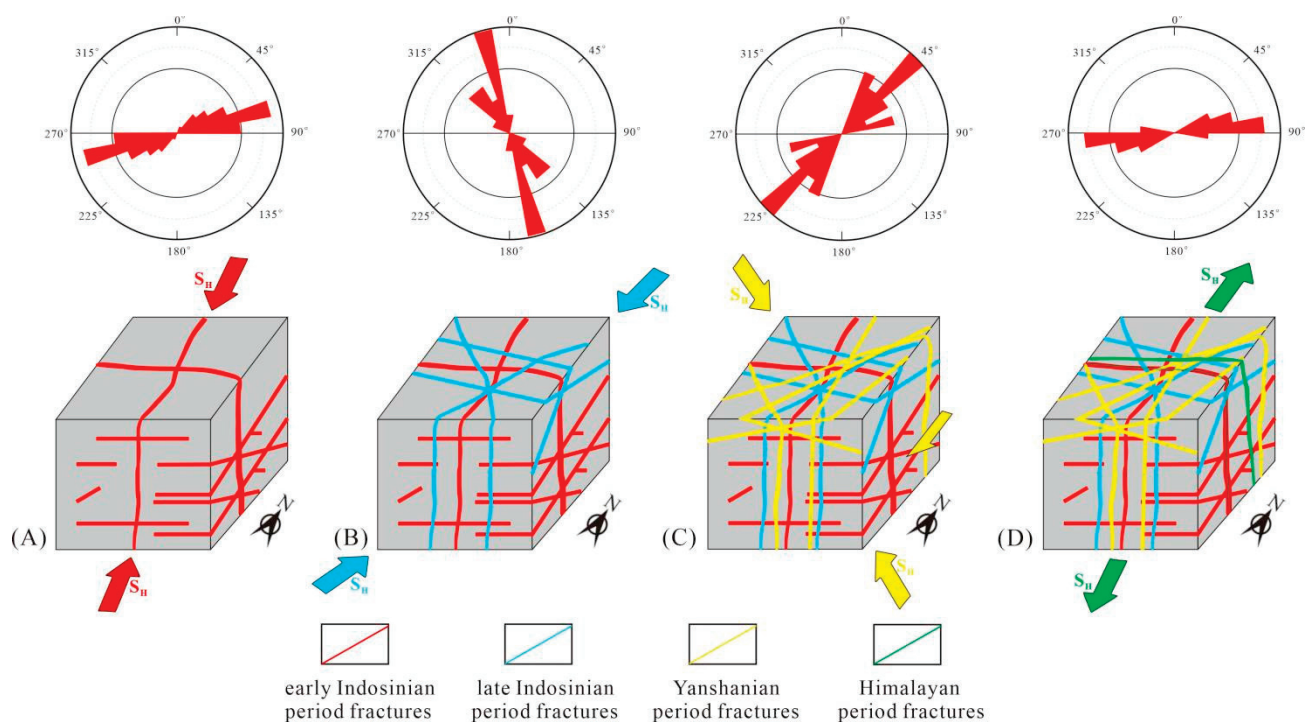


Figure 15. Fracture patterns in metamorphic rocks of the metamorphic basement reservoirs in the Bozhong Depression and Bohai Bay Basin, across different tectonic periods. (A) Rose diagram of early Indosinian fault activity and fracture patterns in metamorphic rocks. (B) Rose diagram of late Indosinian fault activity and fracture patterns in metamorphic rocks. (C) Rose diagram of Yanshanian fault activity and fracture patterns in metamorphic rocks. (D) Rose diagram of Himalayan fault activity and fracture patterns in metamorphic rocks.

During the late Indosinian period, intense NE–SE compressional thrusting further affected the metamorphic basement reservoirs in the study area, leading to the formation of numerous medium- to low-angle NW–SE shear fractures. Additionally, several high-angle shear, high-angle longitudinal extension, and transverse extension fractures also developed (Figure 15B).

During the Yanshanian period, the study area experienced sustained NW–SE compressional forces due to the low-angle subduction of the ancient Pacific Plate beneath the eastern Eurasian margin, combined with the oblique subduction of the Pacific Plate and the distant effects of the Indian Plate's convergence. These forces caused NE-oriented sinistral strike-slip motion. The resulting stress conditions expanded or shifted the Mohr stress circle, increasing the likelihood of fracturing. This led to numerous medium- to low-angle NE–SW shear fractures, along with some nearly S–N high-angle shear fractures, as well as a few high-angle longitudinal and transverse extension fractures (Figure 15C).

During the Himalayan period, the stress field in the Bozhong Depression shifted to a primarily S–N-oriented extensional stress, reactivating preexisting fractures. This reactivation, along with the formation of a few nearly E–W-oriented high-angle tensile fractures, highlights the Himalayan period as a crucial phase in the development of effective fractures within the metamorphic basement reservoirs of the Bozhong Depression (Figure 15D).

5.4. Development Models of Reservoir Fracture Networks and the Role of Natural Fractures in Reservoirs

On the basis of a clear understanding of the fracture characteristics, main controlling factors, mechanical properties, and formation stages of the metamorphic basement reservoirs in the Bozhong Depression, a development model of the fracture network system

has been constructed. The complex lithology of these reservoirs has a significant effect on the distribution of fracture networks. Additionally, a distinct vertical development pattern is observed in the metamorphic basement reservoirs, represented by a two-layer model consisting of a weathering fracture zone and a basement zone. In the weathering fracture zone, fracture development is controlled by both weathering and lithology, resulting in an increased degree of fracture development and a wide range of lithologies, forming a three-dimensional spatial fracture network composed of multiple cataclastic zones.

Fractures in the basement zone are predominantly influenced by fault development caused by tectonic movements. Under similar tectonic stress conditions, layers with a high content of brittle minerals and a low content of plastic minerals are more conducive to the formation of cataclastic zones. Since the Cenozoic, the study area has undergone several phases of tectonic activity, resulting in the formation of a complex fault system and stress field distribution. Fracture development zones are typically located within compressional anticline structures that formed during the Indosinian period as a result of a compressional tectonic setting. Drilling data indicate that rocks such as leptynite and migmatitic granite, which have low plastic mineral content, are well developed and prone to fracturing, thereby making them favorable zones for fracture development within the basement zone.

The metamorphic basement reservoirs in the study area exhibit distinct vertical distribution characteristics. The accumulation of multiple phases of tectonic stress has led to the formation of a three-dimensional network reservoir system, comprising a weathering fracture zone and a basement zone (Figure 16). The weathering fracture zone, located at the top, is influenced by weathering and leaching processes along faults, which facilitate the formation of effective fracture-type reservoirs. Moreover, the deeper basement zone, which is primarily controlled by lithology and multiple phases of tectonic activity, has promoted the development of larger-scale fracture-type reservoirs. This three-dimensional network reservoir system is essential for the formation of extensive, high-quality fracture-type reservoirs within the metamorphic basement of the Bozhong Depression.

Following their formation, the metamorphic basement reservoirs in the Bozhong Depression underwent multiple phases of superimposed tectonic and weathering processes over a prolonged geological evolution, resulting in highly heterogeneous reservoir properties [69]. The storage space in these metamorphic basement reservoirs comprises a dual system of pores and open-mode fractures. The primary porosity is insufficiently developed; thus, the predominant storage spaces are secondary pores. This secondary porosity includes intergranular dissolution pores, intragranular dissolution pores, and pores formed along fractures through dissolution. Additionally, the open-mode fractures consist of both tectonic fractures and certain types of dissolution fractures.

Microscopic observations of thin sections indicate that the apertures of microscale open-mode fractures in metamorphic basement reservoirs are comparable in size to matrix pores. This finding suggests that open-mode fractures are integrated into the pore system and can serve as effective storage spaces. Statistical analysis of 109 thin sections shows that the surface porosity of open-mode fractures in the metamorphic basement reservoirs of the Bozhong Depression ranges from 1.1% to 9.3%, with an average value of 3.1%, accounting for more than 60% of the total surface porosity. Therefore, these open-mode fractures provide effective storage space for oil and gas in metamorphic basement reservoirs.

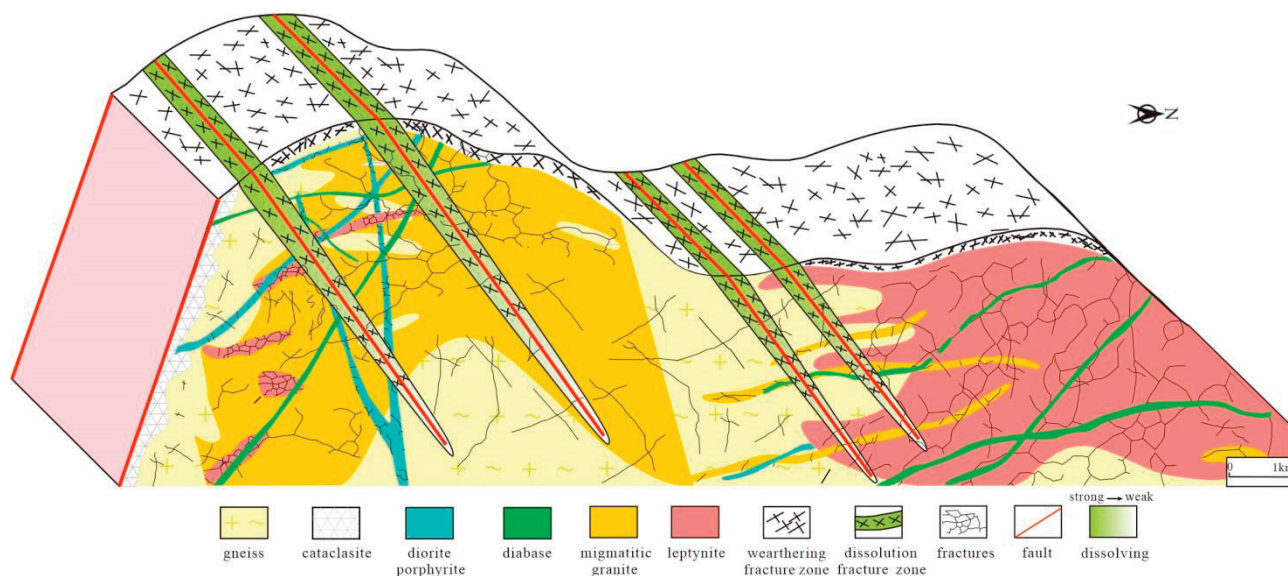


Figure 16. Development model of the fracture network system in metamorphic basement reservoirs of the Bozhong Depression, Bohai Bay Basin. The intense compressional collision during the Indosinian orogeny, combined with left-lateral strike-slip faulting under compressive-torsional forces during the Yanshanian period, resulted in the formation of numerous structural fractures within the metamorphic basement reservoirs. However, fractures were less prevalent in areas located farther from faults or where gneiss formations dominated. Differential uplift during the Indosinian and Yanshanian orogenies led to significant weathering and erosion of the higher regions of the metamorphic basement, where early-stage structural fractures at the reservoir's upper surface were widened by atmospheric freshwater dissolution, forming a weathering fracture zone. Subsequent tectonic activity during the Himalayan orogeny reactivated previously closed and filled faults and fractures, transforming preexisting faults into key pathways for later fluid migration. This process further enlarged the original fractures near the faults through dissolution, leading to the development of internal dissolution fractures.

The widespread development of secondary pores in metamorphic rocks significantly improves the reservoir performance, even in otherwise dense rocks. However, these secondary pores are typically distributed in an isolated manner, which poses challenges for achieving effective connectivity. The multiple phases of open-mode fractures developed in metamorphic basement reservoirs intersect and interconnect, providing favorable pathways for pore connectivity. These results indicate the critical role of fractures in improving the physical properties of metamorphic basement reservoirs and in enhancing fluid flow capabilities. Moreover, the formation of fractures creates advantageous channels for the infiltration of organic acids and meteoric freshwater, establishing a foundation for subsequent dissolution processes [70]. In some cases, fractures underwent intense dissolution along the fracture surfaces after their formation, leading to the development of secondary pores along the fractures. Although some pores in thin sections have experienced a certain degree of filling in later stages, they generally retain effective properties.

The results of core and thin section fluorescence scans revealed prominent hydrocarbons within the fractures (Figure 17), indicating that fractures of various scales provide effective pathways for hydrocarbon migration and significantly improve the quality of metamorphic basement reservoirs, particularly their flow capacity. Additionally, the Bozhong Depression features smaller-scale fractures and pores. Scanning electron microscopy (SEM) observations reveal that these microscale reservoir spaces are more widely distributed and more numerous than macroscopic fractures and pores, playing a similarly critical role in the formation of metamorphic basement reservoirs.

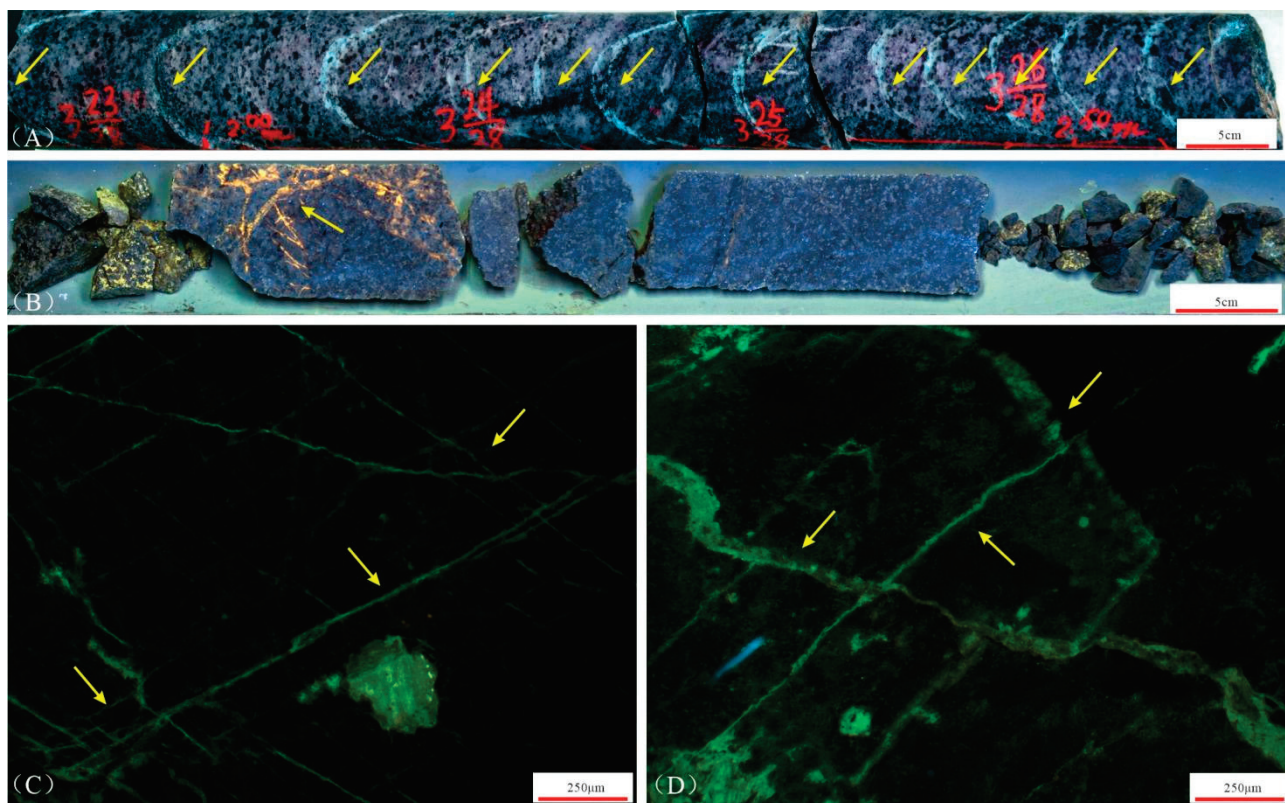


Figure 17. Fluorescence scanning photographs of fractures in cores and thin sections of metamorphic rocks in the Bozhong Depression, Bohai Bay Basin. (A) Fractures containing hydrocarbons in gneiss from Well B19-11 at depths of 5127.6–5128.1 m. (B) Fractures containing hydrocarbons in gneiss from Well B19-12 at depths of 5522.7–5523.3 m. (C) Fractures containing hydrocarbons in gneiss from Well B19-3 at a depth of 3853 m. (D) Interlaced fractures forming a complex fracture network with hydrocarbons present in gneiss from Well B19-3 at a depth of 3850 m.

6. Conclusions

The metamorphic basement reservoirs in the Bozhong Depression, Bohai Bay Basin, feature well-developed natural fractures of various scales, predominantly tectonic fractures, with relatively few dissolution fractures. The degree of fracture development is primarily influenced by lithology, fault activity, and weathering. Tectonic fractures occur more often in metamorphic rocks with higher brittle and lower plastic mineral contents. Consequently, leptynite exhibits the highest average fracture linear density, followed by migmatitic granite and gneiss, while diorite porphyrite and diabase show lower average fracture linear densities. Fractures are more developed at elevated paleogeomorphic positions, with faults significantly controlling fracture orientation.

Owing to the varying extent of fracture development in different lithologies, metamorphic basement reservoirs exhibit distinct vertical zonation. On the basis of the degree of fracture development, the rocks in metamorphic basement reservoirs can be ranked from high to low as follows: leptynite, migmatitic granite, gneiss, cataclasite, diorite porphyrite, and diabase. Rocks ranked higher are more likely to become reservoir rocks in this lithological sequence, whereas those ranked lower typically serve as internal interlayers. In metamorphic basement reservoirs, rocks capable of becoming reservoir rocks generally exhibit a lower limit within this lithological sequence. Diabase represents the lower limit and cannot act as a reservoir rock, whereas rocks preceding diabase have the potential to become reservoir rocks under certain geological conditions.

The compressional effects of several phases of tectonic activity laid the foundation for the formation of tectonic fractures in the metamorphic basement reservoirs of the Bozhong Depression. The large-scale compressional orogeny during the Indosinian period marked the primary phase of tectonic fracture formation. Subsequent uplift and inversion during the Yanshanian period further modified and overlaid the Indosinian structures. These structures are characterized by strong strike-slip strain, resulting in a series of conjugate shear fractures. The Himalayan period primarily reactivated preexisting fractures, which significantly influenced fracture effectiveness.

The fracture network system in the studied metamorphic basement reservoirs is shaped by a coupling mechanism between dominant lithology and multiphase fracturing. Weathering and fault systems promote fracture development in the weathering zone, while the superposition of multistage tectonic stresses and lithological heterogeneity forms the basis for the development of large fracture zones in the basement zone. This three-dimensional network, consisting of weathering and basement zones, is essential for creating large-scale reservoirs. The important storage spaces are open-mode fractures and dissolution pores along fractures, which increase connectivity and improve reservoir quality. Multiscale natural fractures exert a controlling influence on hydrocarbon migration and accumulation in the metamorphic basement of the Bozhong Depression.

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Article

Pore Structure Characteristics and Genesis of Low-Permeability Sandstone Reservoirs in the Eocene Wenchang Formation, Huizhou Sag, Pearl River Mouth Basin, Northern South China Sea

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Abstract: Porosity and permeability are critical parameters in petroleum exploration and development. The relationship between pore structure and permeability in near-source reservoirs is more closely correlated than in other types of reservoirs. This study investigates the pore structure and formation processes of low-permeability sandstone reservoirs in the Wenchang Formation, Huizhou Depression, Pearl River Mouth Basin (Northern South China Sea). We collected ten core samples of low-permeability sandstone reservoirs at various depths from the key well (A). Multiple analytical techniques were employed, including mercury intrusion capillary pressure (MICP), constant velocity mercury injection (CMI), Wood's metal impregnation (WM), scanning electron microscopy (SEM), X-ray diffraction (XRD), and quantitative evaluation of minerals via scanning electron microscopy (QEMSCAN). Pore-throat types were classified using fractal theory, followed by analyzing the physical and structural characteristics of interconnected pore-throat reservoir systems. This study examined the impact of various pore types on the physical properties of reservoirs, providing a comprehensive classification and characterization of pore structures in low-permeability sandstone reservoirs. Our findings provide significant insights and recommendations for future developmental initiatives in this region.

Keywords: sandstone; permeability; pore throat; unconventional reservoirs; fractal theory; formation heterogeneity

1. Introduction

Low-permeability sandstone reservoirs have emerged as critical global oil and gas exploration targets [1]. These unconventional resources, characterized by micro-to-nanoscale pore-throat structures, represent a substantial portion of the remaining hydrocarbon reserves worldwide [2]. In North America, technological innovations have facilitated remarkable advancements in developing these challenging reservoirs [3]. While China's exploration of low-permeability sandstone reservoirs began relatively later, it has achieved significant progress in recent years, with the Changqing Oilfield in the Ordos Basin serving as an exemplary case of both technological innovation and practical application [4].

The fundamental distinction between low-permeability sandstone reservoirs and conventional reservoirs lies in their pore-throat structures, which directly influence fluid storage capacity, flow behavior, and hydrocarbon accumulation and distribution patterns [5]. Consequently, comprehensive characterization of pore structures and connectivity in low-permeability reservoirs is essential for understanding the mechanisms governing hydrocarbon migration, accumulation, and production potential.

Low-permeability sandstone reservoirs are distinguished by their complex pore-throat systems, typically ranging from nanometers to micrometers in size [6]. These reservoirs exhibit several distinctive characteristics: (1) intricate, tortuous pore-throat networks with complex geometries; (2) restricted pore radii, often below 1 μm ; (3) limited pore-throat connectivity; (4) pronounced heterogeneity in spatial distribution; and (5) complex relationships between porosity and permeability [7].

The microstructural properties of these reservoirs significantly impact fluid storage capacity and transmissibility [8]. Unlike conventional reservoirs, where the relationship between porosity and permeability follows relatively predictable patterns, low-permeability sandstones often exhibit complex, non-linear relationships between these parameters [9]. This complexity necessitates detailed analysis of pore morphology, size distribution, and connectivity to accurately predict reservoir performance and optimize development strategies [10].

Researchers have employed diverse methodologies to characterize the pore size distribution (PSD) and geometry of sandstone reservoirs, which can be categorized into three principal approaches: imaging methods, ray scanning methods, and fluid injection methods [11]. Techniques such as casting thin sections and scanning electron microscopy (SEM) provide valuable insights into pore morphology, size, and genetic origin [12]. These methods offer high-resolution visualization of pore spaces. Still, they are inherently limited by their two-dimensional nature and the specific area being imaged, potentially leading to sampling bias and incomplete characterization of the entire pore network [13]. Computed tomography (CT) scanning enables three-dimensional visualization of pore distributions within core samples. This technique quantifies parameters such as pore size, pore number, and pore-throat ratios. However, resolution limitations may prevent the accurate characterization of nanoscale features critical to low-permeability reservoirs [14]. The fluid injection techniques represent the most widely applied and effective approaches for analyzing low-permeability sandstone reservoirs, such as gas adsorption (utilizing N_2 and CO_2), mercury intrusion capillary pressure (MICP), and constant-velocity mercury injection (CMI) [15].

Despite these advances, no analytical method can comprehensively characterize the complex pore structures of low-permeability sandstone reservoirs. A multi-technique integrated approach is necessary to overcome the limitations of individual methods and provide a holistic understanding of reservoir characteristics.

Despite considerable research on low-permeability sandstone reservoirs globally, several knowledge gaps persist: (1) limited studies have focused on the Wenchang Formation within the Huizhou Depression of the Pearl River Mouth Basin, despite its significant hydrocarbon potential; (2) the relationship between pore structure characteristics and reservoir quality in this specific geological context remains inadequately understood; (3) previous investigations have often employed single analytical techniques, potentially overlooking the complex interplay of factors affecting pore structure and connectivity; and (4) the application of fractal theory to classify pore-throat types in this region has not been thoroughly explored.

These knowledge gaps highlight the need for a comprehensive, multi-method investigation of the pore systems in low-permeability sandstone reservoirs of the Wenchang Formation. The primary objective of this study is to characterize the pore structure and

genesis of low-permeability sandstone reservoirs in the Wenchang Formation within the Huizhou Depression of the Pearl River Mouth Basin in the Northern South China Sea. Specific aims include the classification of pore-throat types using fractal theory, detailed analysis of the physical and structural characteristics of interconnected pore-throat reservoir systems, assessment of the influence of each pore type on reservoir physical properties, and development of recommendations for future exploration and development strategies. This study employs an integrated analytical approach combining (Figure 1) mercury intrusion capillary pressure (MICP), constant-velocity mercury injection (CMI), Wood's metal impregnation (WM), scanning electron microscopy (SEM), X-ray diffraction (XRD), and Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) to achieve these objectives [16]. This multi-method approach enables the comprehensive characterization of pore systems across multiple scales, from nanometers to micrometers, providing insights that would be unattainable through any single analytical technique. This study presents a comprehensive investigation of pore structure characteristics in low-permeability sandstone reservoirs of the Wenchang Formation, employing an integrated analytical approach. Our findings will enhance the understanding of the fundamental controls governing reservoir quality within the study area, facilitate the development of more accurate predictive models for reservoir performance, and optimize exploration and development strategies for analogous low-permeability sandstone reservoirs. This study also presents advanced methodological approaches for characterizing complex pore systems in unconventional reservoirs. By presenting a detailed classification and description of pore structure characteristics, this research will provide invaluable insights and practical recommendations for the prospective development of hydrocarbon resources in the Huizhou Depression of the Pearl River Mouth Basin.

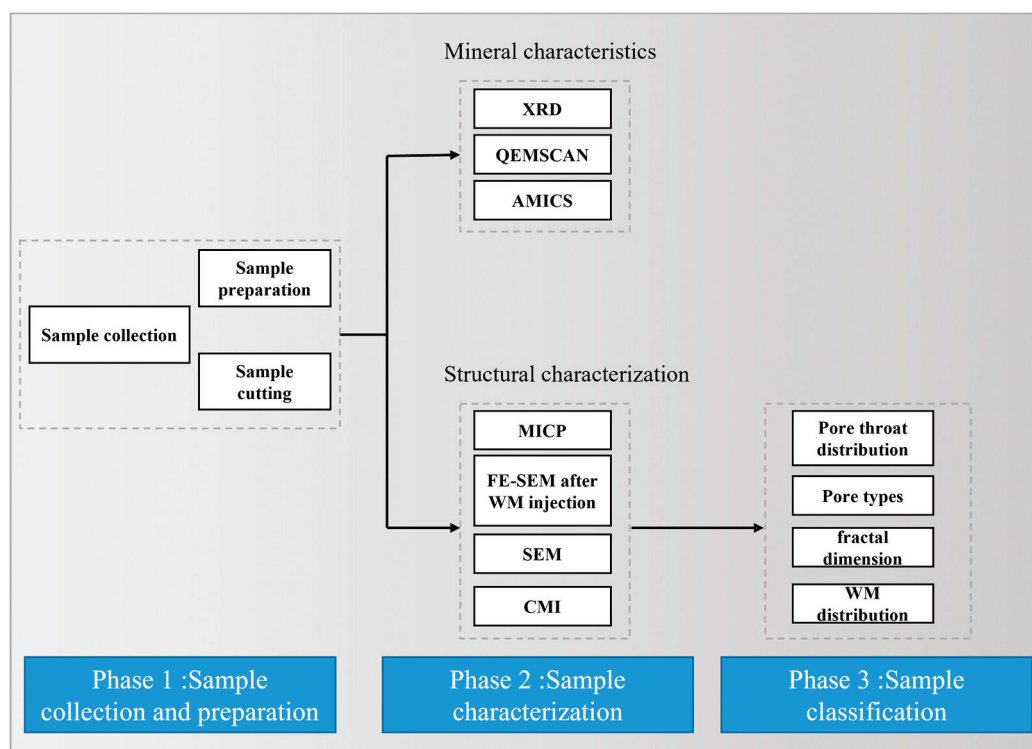


Figure 1. Experimental procedure followed in this work.

2. Geological Background of the Pearl River Mouth Basin

The Huizhou sag of the Pearl River Mouth Basin is located in the eastern region of the South China Sea (Figure 2), encompassing an area of approximately $1.75 \times 10^5 \text{ km}^2$. This

significant Mesozoic–Cenozoic sedimentary basin was developed on Yanshanian granite and a pre-Cenozoic folded basement [17]. The basin possesses rich oil and gas resources, rendering it one of the most productive petroliferous basins in the South China Sea. It is categorized from north to south into the Northern Uplift Belt, Northern Depression Belt, Central Uplift Belt, Central Depression Belt, Southern Uplift Belt, and Southern Depression Belt [18]. The Huizhou Sag is geographically positioned in the central area of the Northern Depression Belt within the Pearl River Mouth Basin. The Paleogene strata within this region, arranged from top to bottom, include the Wenchang Formation, Enping Formation, and Zhuhai Formation. With burial depths exceeding 3000 m, the Paleogene sequences in the Huizhou Sag have experienced extended sedimentation and intricate diagenetic alteration processes. These phenomena have resulted in complex reservoir property evolution, as well as diverse mechanisms and factors influencing the development of effective reservoirs, ultimately leading to significant heterogeneity in reservoir distribution [19].

The Cenozoic of the Huizhou Sag is based on pre-Paleogene metamorphic rocks and volcanic rocks, and the thickness of sedimentary strata is generally about 5000 m. The sedimentary environment of the Huizhou Sag has undergone an evolution process from continental lakes to deltas to sea transgressions [20]. During the Paleogene period, the area was mainly lacustrine sedimentary environment, and the sediments were mainly mudstone and siltstone. In the Neogene period, with the intensification of transgression, the sedimentary environment became delta sedimentary, and the sediment types included sandstone, mudstone, coal seam, etc. [21]. During the Quaternary period, the transgression was further expanded, forming a sedimentary environment dominated by sand and gravel.

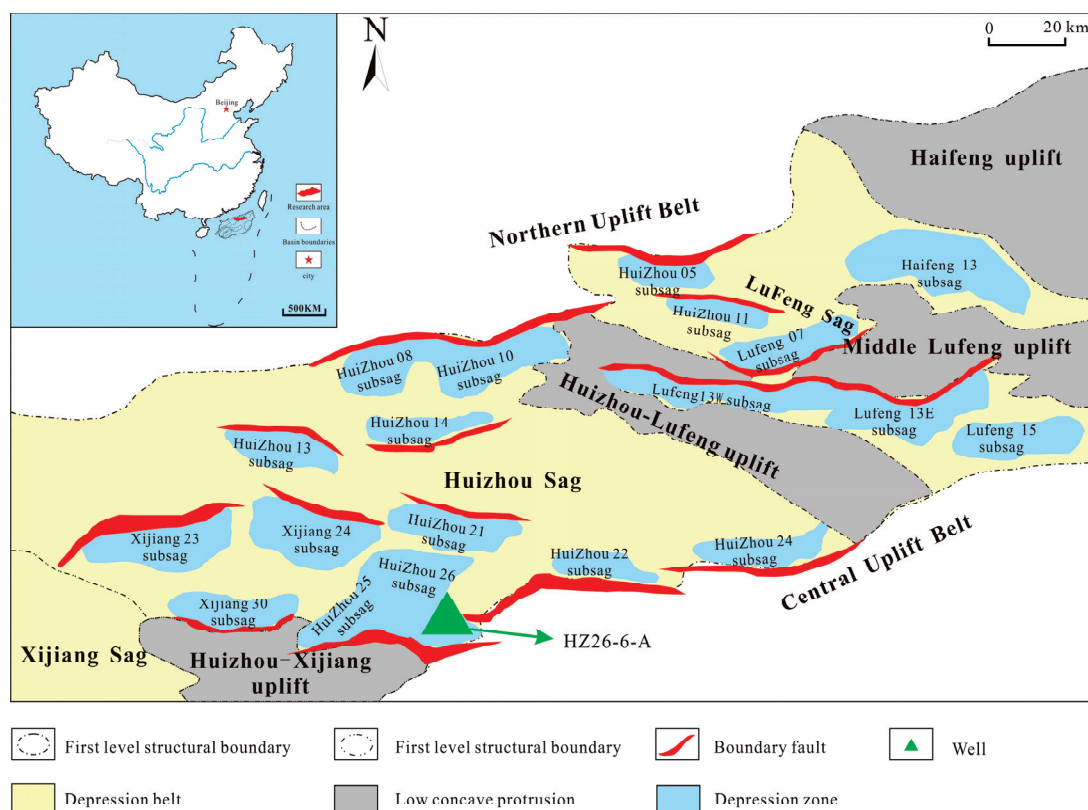


Figure 2. Structural division and location of the study area in the Pearl River Mouth Basin [15].

3. Materials and Methods

3.1. Sample Characterization and Preparation

To investigate the characteristics and genesis of the pore structure of low-permeability sandstone from the Wenchang Formation, we collected the sandstone samples from key well (A) in the Huizhou sag of the Pearl River Mouth Basin. Through core observation, as illustrated in Figure 3, ten plug samples, each 2.5 cm in diameter and 5 cm in length, were extracted from core samples at varying depths for a series of experimental analyses. The PDP-200 overburden porosimeter–permeameter (CoreLab, Amsterdam, The Netherlands), utilizing helium, was employed to ascertain the porosity and permeability of each plug sample under a confining pressure of 800 psi at room temperature (Table 1). All plug samples were subsequently reduced to cubic shapes (approximately 1 cm³) for MICP, CMI, and high-pressure Wood’s metal impregnation experiments. Each cubic sample underwent oven drying at 60 °C for a duration exceeding 48 h to remove moisture and volatiles before the commencement of the experiments. The granularity, petrography, and mineralogy of the samples were analyzed through the observation of thin sections and X-ray diffraction (XRD). Crushed samples, with a particle size of less than 200 mesh, along with clay minerals extracted via the gravity method, were examined using an X-ray diffraction instrument to determine the mineral composition. The granularity. The content of quartz, feldspar, and rock fragments within the sandstone was assessed by preparing thin sections to classify the sandstone petrography.

3.2. MICP Measurement

MICP tests were performed using a Micromeritics AutoPore IV 9620 Porosimeter (Micromeritics® Instruments, Norcross, GA, USA), with an initial injection pressure of 0.5 psi (0.0034 MPa), to determine the bulk density of the samples. The maximum intrusion pressure of 60,000 psi (413.7 MPa) was used to obtain the cumulative intrusion pore volume, which was then used to calculate the skeletal density and porosity of the samples. According to the Washburn equation ($p = 2\sigma \cos \theta / r$, where r is the pore-throat radius, p is the intrusion pressure, θ is the contact angle set at 130°, and σ is the surface tension set at 485 mN/m), the pore throat detected in the experimental pressure ranges from 340 µm to 3 nm. Before the MICP tests, six surfaces of each cubic sample were polished to reduce the pockmark effects during the test. A penetrometer with a capillary volume of 0.412 mL (measuring samples with porosity between 2% and 30%) was selected for the low-permeability sandstone sample.

3.3. CMI Test

CMI tests were performed on an ASPE-730 instrument (Micromeritics® Instruments, Norcross, GA, USA), using a constant rate of 5×10^{-5} mL/min to drive mercury into the sandstone sample in a quasi-static process, increasing the pressure from 0.7 psi to 900 psi, corresponding to a pore/throat range of 280 µm to 200 nm. The difference between CMI and MICP is that CMI can distinguish the distribution of pore size and throat size in sandstone samples through the change in pressure. When mercury fills the pore space through the throat, the pressure will decrease and fluctuate, and the increase in mercury intrusion resulting from the pressure jump corresponds to the pore volume (Figure 4). Assuming that the pore is spherical in shape, the pore radius can be calculated, and the size distribution of tubular throat and spherical pore can be obtained.

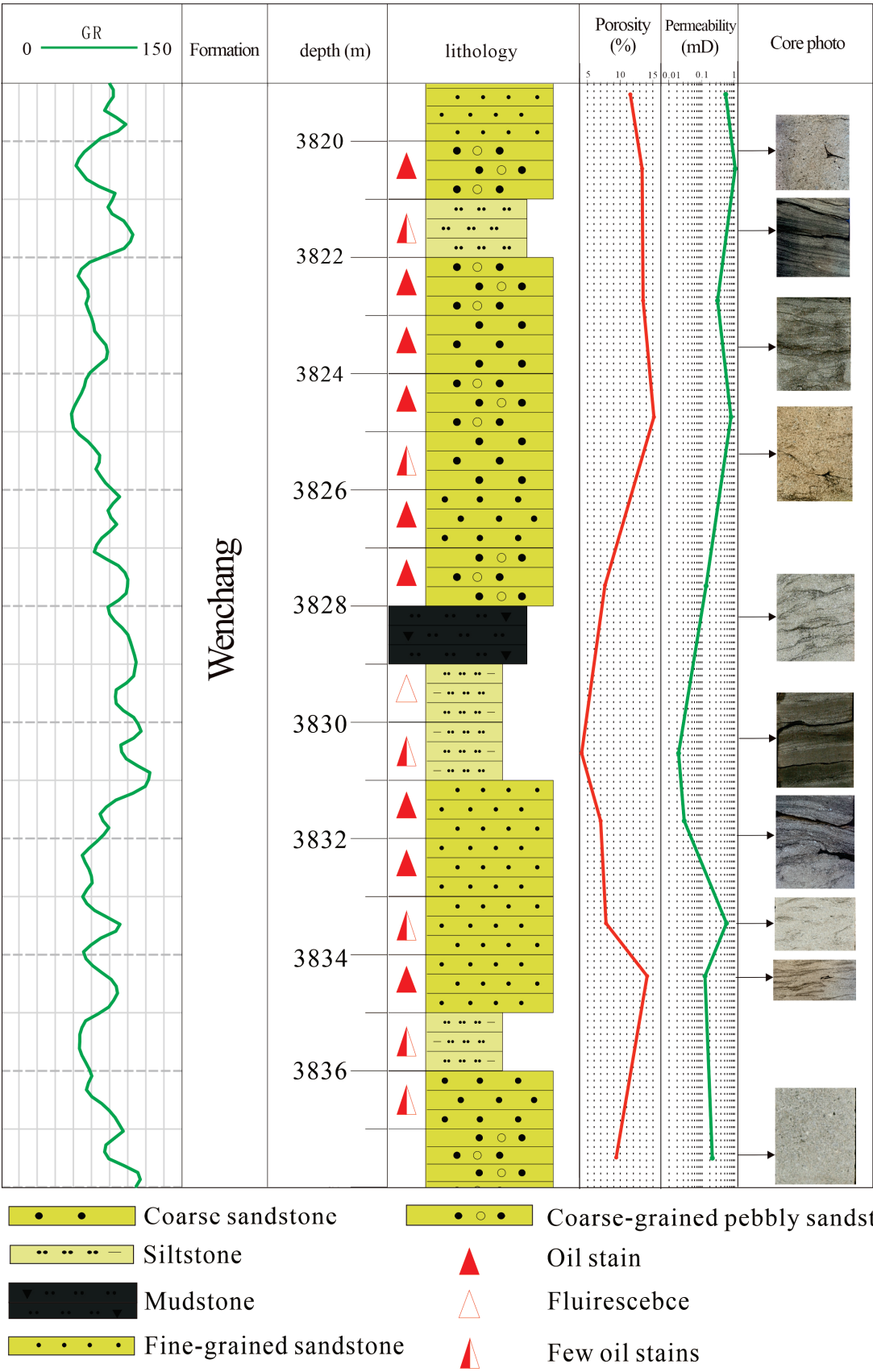
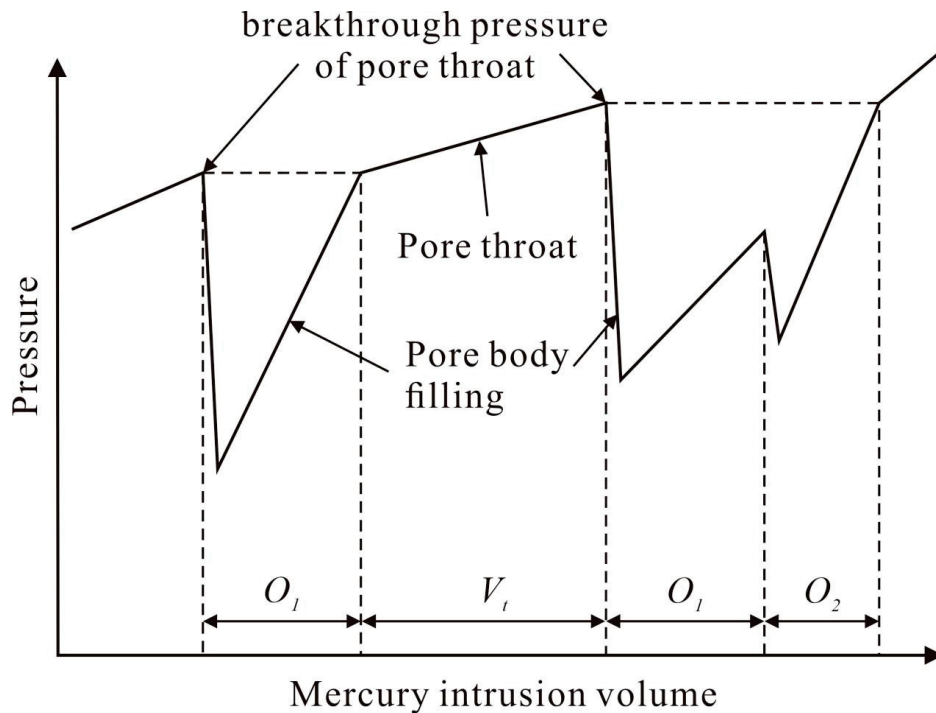


Figure 3. Core columnar diagram of the study area in Huizhou.

Table 1. Granularity, physical properties, and mineral components of low-permeability sandstone samples from the Eocene Wenchang Formation.

Sample	Depth (m)	Granularity	Porosity (%)	Permeability (mD)	Whole-Rock X-Ray Diffraction (XRD) (wt.%)					Clay Minerals in X-Ray Diffraction (XRD) (wt.%)				
					Quartz	Feldspar	Calcite	Barite	Clays	I/S	I	K	C	%S
A-1	3820.15	Pebbly, coarse-grained	11.5	0.580	66	25	4	0	5	19	6	10	65	10
A-2	3821.40	Pebbly, coarse-grained	13.4	1.060	62	23	7	0	8	18	5	7	70	10
A-3	3823.50	Inequigranular	13.5	0.358	75	18	3	0	4	12	8	8	72	10
A-4	3825.41	Medium- coarse-grained	15.1	0.723	71	19	3	0	7	25	27	8	40	10
A-5	3828.12	Coarse-grained	7.8	0.144	48	30	14	2	6	7	8	12	73	10
A-6	3830.86	Inequigranular	3.2	0.026	32	40	24	2	2	30	17	37	16	10
A-7	3831.96	Inequigranular	7.2	0.039	50	39	4	2	5	15	8	12	65	10
A-8	3833.68	Inequigranular	7.8	0.433	58	27	5	2	8	22	17	6	55	10
A-9	3834.49	Inequigranular	14.1	0.113	62	27	7	0	4	11	16	14	59	10
A-10	3837.43	Coarse-grained	11.4	0.230	70	24	2	0	4	17	13	10	60	10

I/S = illite-smectite mixed-layer mineral; I = illite; K = kaolinite; C = chlorite; %S = percentage of smectite in mixed-layer mineral 3.2. MICP measurement.



O_1 --Primary pores, O_2 --Secondary pores; V_t --Pore throat volume

Figure 4. Schematic diagram of the constant-rate mercury injection (CRMI) principle.

3.4. FE-SEM Observation After WM Impregnation

The WM impregnation experiments were performed using a self-developed WM injection apparatus (Figure 5) at the State Key Laboratory of Continental Shale Oil, affiliated with Northeast Petroleum University. The oven-dried cubic sample and WM were placed in the high-pressure sample cell of the WM injection apparatus, which was heated to 110 °C under vacuum conditions to melt the WM (melting point: 80 °C) and wrap the sample. Then, the pressure in the high-pressure sample cell was increased by a hand pump at a rate of 3 MPa/min to 200 MPa and maintained at maximum pressure for one hour to fill the pore space of the sample with the liquid WM. After that, the sample cell was cooled to room temperature while maintaining a pressure of 200 MPa, allowing WM to solidify in the pore space of the sample. Finally, removed from the high-pressure cell after depressurization to ambient conditions and cut in half from the middle to obtain the internal surface of the sample (1 cm²), the WM (40% Bi; 30% Sn; 20% Pb; 10% Cd) used in this study had a surface tension of 420 mN/m in the molten state and a contact angle of 110° on the sample surface. Therefore, according to the Washburn equation, the lower limit of pore throat that can be injected into WM at 200 MPa is approximately 3 nm.

To obtain a smooth surface for FE-SEM observation and AMICS analysis, the observation surface was polished using an argon-ion polisher (Ilion+ II, Model 697, GATAN) at 50 °C, with liquid nitrogen used to prevent the WM from melting. The smooth surfaces were imaged and analyzed for minerals using a field-emission FEI Quanta 650 scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS). The FE-SEM images were quantitatively analyzed using ImageJ (V1.8.0.112) software to obtain pore structure information of the sandstone.

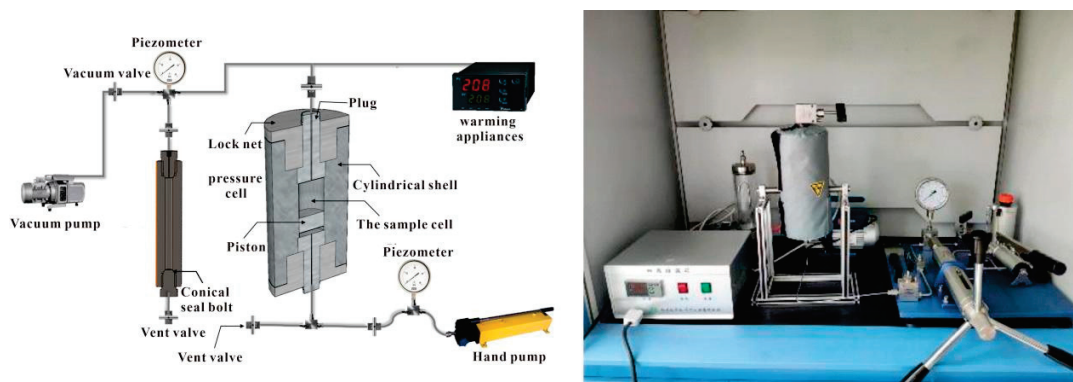


Figure 5. Schematic diagram of Wood's metal apparatus.

AMICS analysis can identify mineral components and fill WM by scanning the smooth surface of the sample. AMICS analysis was performed using a Zeiss Sigma 300 FE-SEM (Carl Zeiss AG, Oberkochen, Germany), combined with a Bruker Xflash 6/60 energy-dispersive X-ray spectroscopy (Bruker, Berlin, Germany), to quantitatively characterize the components of the sample surface with a resolution of 1 μm . Because the pebbly, coarse-grained sandstone contains grains larger than 2 mm in size, the field-of-view area scanned by the sample is greater than 25 mm² to represent the overall characteristics of the sample. The associative relationship between the WM filling pores and minerals, as well as the contact relationship between different minerals, can be visualized and quantified using AMICS analysis.

4. Results

4.1. Petrological and Mineralogical Characteristics

The grain size, physical properties, and mineral composition of 10 samples from well A are detailed in Table 1. Although the samples are from a narrow range of depths, there is considerable variation in porosity and permeability, ranging from 3.2% to 14.1% and from 0.026 mD to 1.060 mD, respectively. The average porosity is 10.5%, with an average permeability of 0.3706 mD. These results indicate that the interval in well A exhibits significant heterogeneity and is characteristic of a typical low-porosity, low-permeability reservoir.

Figure 6 presents the results of whole-rock mineral analysis. The data indicate that quartz is the predominant mineral component, with its content ranging from 32 wt.% to 75 wt.% and an average content of 59.4 wt.%. Additionally, the feldspar content varies from 13 wt.% to 40 wt.%, with most samples containing a higher proportion of K-feldspar than plagioclase. Samples exhibited calcite contents ranging from 2 wt.% to 24 wt.%, with those having higher calcite contents typically exhibiting lower quartz levels. Barite was present only in the four samples with the lowest quartz content, at 2 wt.%; it was absent from all other samples.

The clay mineral content is relatively low, ranging from 2% to 8%, with an average content of 5.3%. Through thin-section observation and statistical analysis of rock composition (Figure 6a), combined with Folk's classification scheme [22], the lithologies of Wenchang low-permeability sandstone reservoirs mainly consist of lithic arkose and feldspathic litharenite, with a small amount of sublitharenite (Figure 6c).

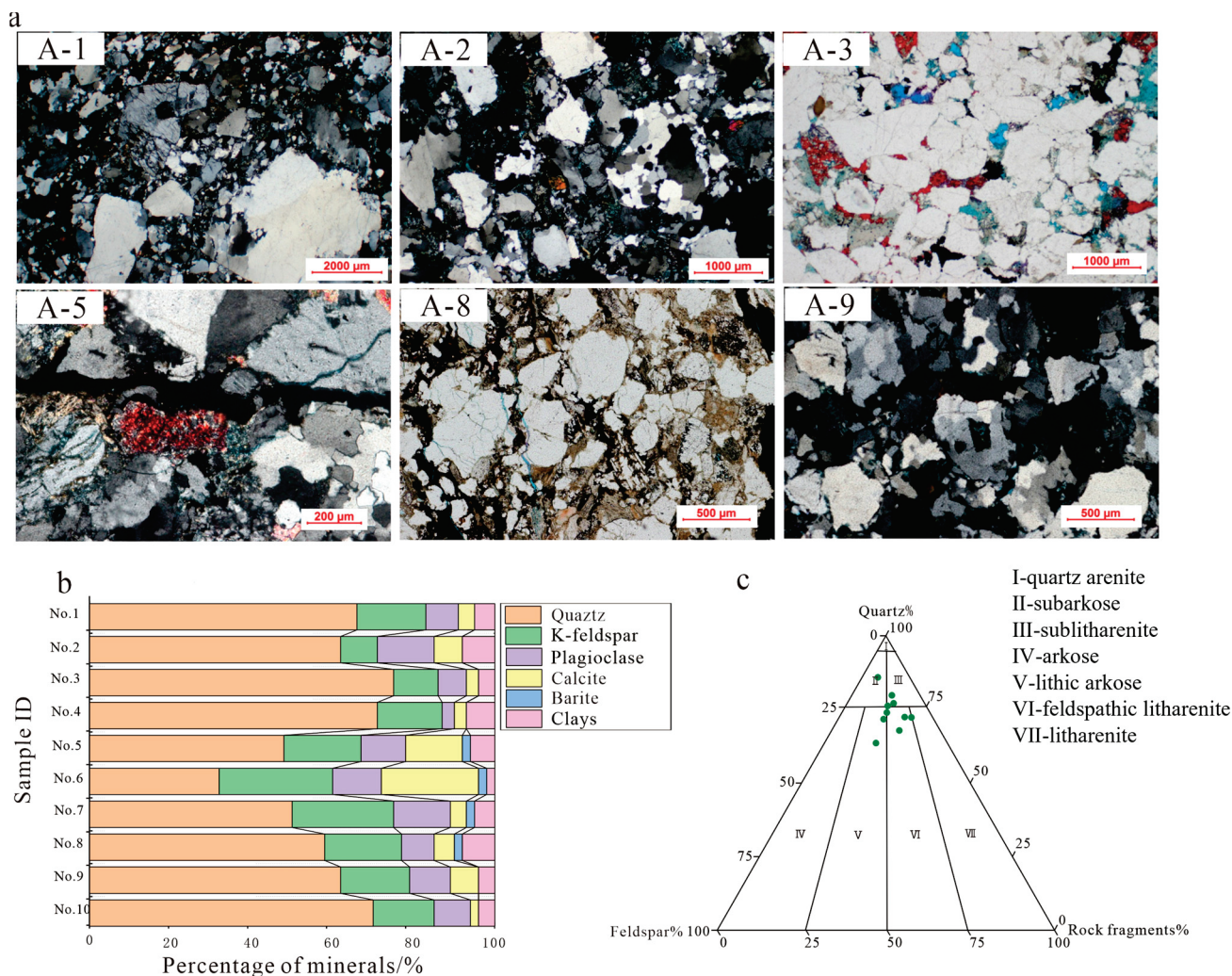


Figure 6. Selected samples of cast thin-section microscopic observations (a); statistics on the content of major minerals, such as quartz and feldspar (b); and sandstone classification triangulation (c).

4.2. MICP

The structural parameters of the pore throats of the 10 sandstone samples in the study area for the MICP experiment are shown in Table 2. The porosity ranges from 3.19% to 14.09%, with an average of 9.285%, which is generally lower than that of helium porosity (Table 1) because the pore throats of MICP tests range from 7.25 nm to 105.00 μm . The range of the pores of from the helium porosity tests is much larger than the pore-throat interval of the MICP tests. The displacement pressures of the 10 samples were significantly different, with discharge pressures ranging from 0.16 MPa to 0.67 MPa. The maximum mercury saturation and mercury withdrawal efficiency reflect the reservoir's collectability and connectivity. The average maximum mercury saturation in the study area is 89.9%, which is higher than that of conventional low-permeability reservoirs, indicating that the study area has better hydrocarbon storage capacity. The average mercury withdrawal efficiency is 22.6%, reflecting the relatively poor pore connectivity of the reservoir in the study area.

In this study, the pore-throat structures of ten sandstone samples from the study area were quantitatively analyzed using high-pressure mercury intrusion porosimetry (MICP), and fractal theory was employed to calculate the fractal dimension (D) to distinguish between different types of pore structures.

Table 2. Pore parameters of low-permeability sandstone samples obtained from MICP.

Sample ID	Bulk Density (g/cm ³)	Porosity (%)	Maximum Mercury Saturation (%)	Displacement Pressure (MPa)	Mercury Withdrawal Efficiency (%)	Total Pore Area (cm ² /g)	Fractal Inflection Point 1 (μm)	Fractal Inflection Point 2 (nm)
A-1	2.38	7.91	68.78	0.25	28.22	1.61	2.5	120
A-2	2.27	9.26	69.10	0.16	23.44	1.98	4.7	106
A-3	2.37	12.57	93.11	0.20	21.73	1.85	3.1	120
A-4	2.30	13.02	86.23	0.22	19.48	2.16	3.7	95
A-5	2.49	6.73	86.28	0.22	24.29	1.59	2.5	95
A-6	2.69	3.19	99.7	0.67	19.10	1.77	1.0	29
A-7	2.45	6.97	96.8	0.44	26.10	3.67	2.1	32
A-8	2.65	7.76	99.5	0.57	24.32	1.39	1.0	69
A-9	2.28	14.09	99.9	0.27	19.09	2.65	3.1	50
A-10	2.42	11.35	99.6	0.26	20.30	1.65	3.1	62

4.2.1. Determination of Total Pore Volume

The total pore volume (V_p) of the samples was determined using helium porosity. Due to its small atomic radius, helium can effectively penetrate even the finest pores within the sample, precisely measuring the total pore volume. This method ensures that the volume of all connected pores is accurately determined, providing a reliable basis for subsequent mercury saturation calculations.

4.2.2. Calculation of Mercury Saturation

During the MICP experiment, mercury is incrementally intruded into the pore system of the samples by applying increasing pressure, and the corresponding mercury intrusion volume ($V_{Hg}(P)$) is recorded at each pressure point. The mercury saturation ($S_{Hg}(P)$) at a given pressure (P) is defined as the ratio of the mercury-occupied pore volume to the total pore volume, and it is calculated using the following equation:

$$S_{Hg}(P) = \frac{V_{Hg}(P)}{V_p} \times 100\% \quad (1)$$

where $V_{Hg}(P)$ is the cumulative mercury intrusion volume at pressure, P ; and V_p is the total pore volume measured by helium porosity.

4.2.3. Calculation of Fractal Dimension

The relationship between mercury saturation ($S_{Hg}(P)$) and pressure (P) was transformed into a linear relationship in a logarithmic coordinate system, expressed as $\log(1 - S_{Hg})$ versus $\log(P)$.

The slope of the linear fit obtained through this transformation is the negative of the fractal dimension, D :

$$\log(1 - S_{Hg}) = -D \cdot \log(P) + C \quad (2)$$

where C is a constant; and the magnitude of the fractal dimension, D , reflects the self-similarity and complexity of the pore-throat structure.

4.2.4. Segmented Linear Fitting

In the MICP experiments, the mercury saturation curves typically exhibit multiple linear segments across different pressure ranges. To accurately describe the fractal charac-

teristics of pore throats at different scales, the curves were subjected to segmented linear fitting, and the fractal dimension, D , was calculated for each segment. This segmented approach allows for the differentiation of pore-throat structural features under varying pressure conditions, providing a more detailed quantification of reservoir heterogeneity.

Figure 7a presents the mercury intrusion and extrusion curves for a representative sandstone sample from the ten samples collected from the Huizhou area. The high-pressure mercury intrusion experiment was conducted within a pressure range of 0.0069 MPa to 101 MPa, and the sample exhibited a porosity of 7.91%. The figure also reveals a mercury withdrawal efficiency of 28.22% for this sample.

Based on the porosity measurements obtained from mercury intrusion porosimetry and helium porosimetry, the capillary pressure curve of the sample was generated, as illustrated in Figure 7b. The analysis indicates that the sample's maximum mercury saturation reached 67.78%, with a displacement pressure of 0.25 MPa.

Analysis of the fractal characteristic curve in Figure 7c reveals that the sample exhibits a distinct tri-segmental distribution pattern, with each segment corresponding to a distinct fractal dimension value. This tripartite structure demonstrates that the pore space can be divided into three distinct systems. The application of the Washburn equation enables the quantitative determination of throat diameters corresponding to each pressure stage, with the ranges of the three throat types illustrated in Figure 7d.

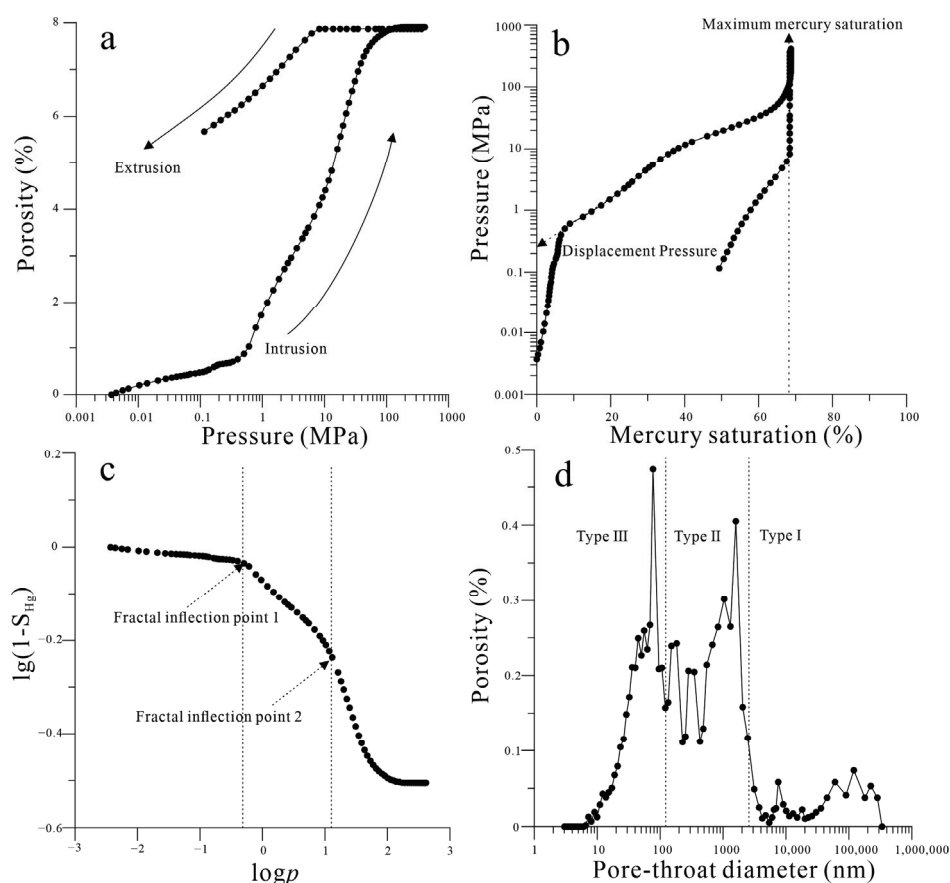


Figure 7. MICP piecewise linear fit curve. (a) Mercury injection–withdrawal curves. (b) The capillary pressure curve. (c) The fractal characteristic curve. (d) Throat size distribution curve.

The pore structures in the study area can be classified into three main types based on the proportional distribution of different pore types. The first type (type I) is characterized by intergranular pores (Samples 3, 4, 9, and 10), which exhibit significantly higher porosity, greater cumulative mercury intrusion, and lower displacement pressure, indicating better

connectivity and, consequently, higher permeability. The second type (type II) exhibits a dual-porosity system with both intergranular and intragranular pores (Samples 1, 2, and 8), showing moderately lower porosity and cumulative mercury intrusion than the first type, along with a relatively uniform pore size distribution that reflects a balanced bifractal structure. The third type (type III) is primarily controlled by intragranular pores (Samples 5, 6, and 7), demonstrating the lowest cumulative mercury intrusion and porosity (Figure 8). Due to the small and irregularly distributed pore-throat diameters, this type exhibits the poorest connectivity, resulting in the lowest permeability.

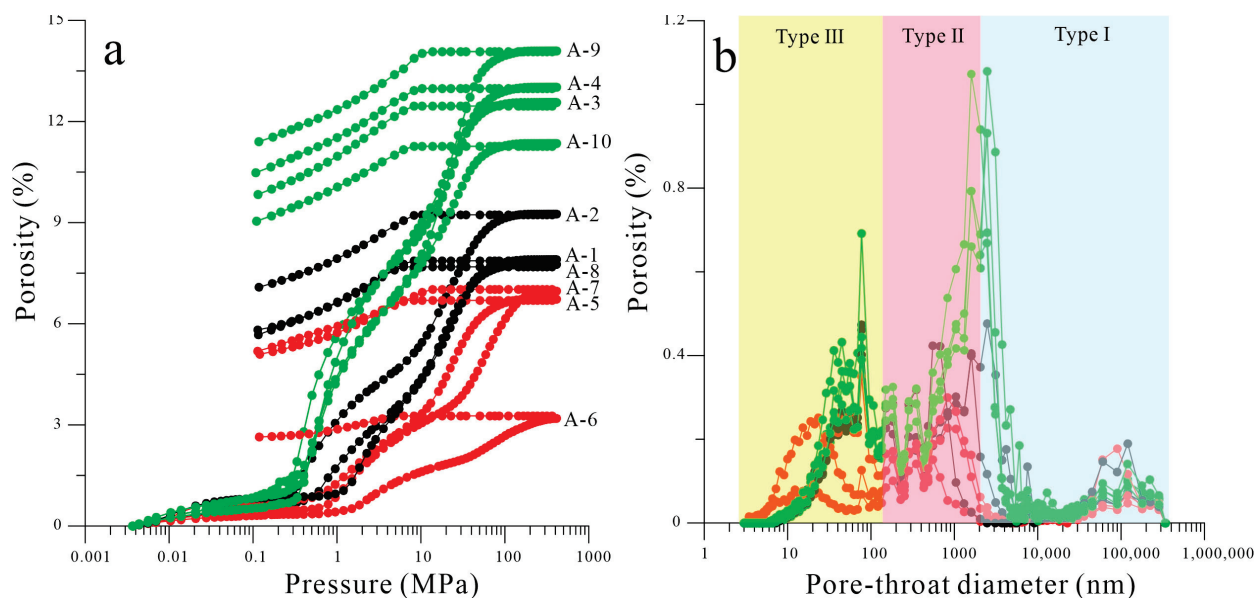


Figure 8. (a) Mercury injection–withdrawal curves. (b) Throat size distribution curve.

4.3. CMI

The figure illustrates the Hg intrusion curves from CMI tests of six sandstone samples (including pores, throats, and total pores). The pressure profiles can be categorized into three types based on the intrusion characteristics of Hg in the pores. In the first type of samples, the total intrusion curves show a short “plateau trend” in the low-pressure stage, during which most of the Hg enters into the pores, and only a small portion of the Hg enters into the throats (Figure 9a,b), suggesting that the pore types of this type of sample belong to the category of “large pores and narrow throats”, and the pores are mainly composed of large pores with narrow throats. This indicates that the pore type of these samples belongs to “large pores and narrow throats”, and the pores are mainly dominated by intergranular pores, and in the stage of pressure rise, the mercury only enters into the smaller pores and throats. The second type of samples and the first type of samples have a similar plateau area, but the second type of samples has less pore space, and the mercury mainly enters into the throat during the pressure-rise stage, indicating that the pore type belongs to the “medium pore space and narrow throat”, and the pore space consists of a small portion of intergranular pores and a portion of intragranular pores (Figure 9c,d). In the third type of samples, there is no plateau period, and Hg enters the throat only when the pressure reaches a certain level. The pore type of the third type of samples belongs to the “narrow throat with small pores”, and there is no obvious difference between the pore body and the throat, indicating that the pore related to the intragranular pores is dominant (Figure 9e,f).

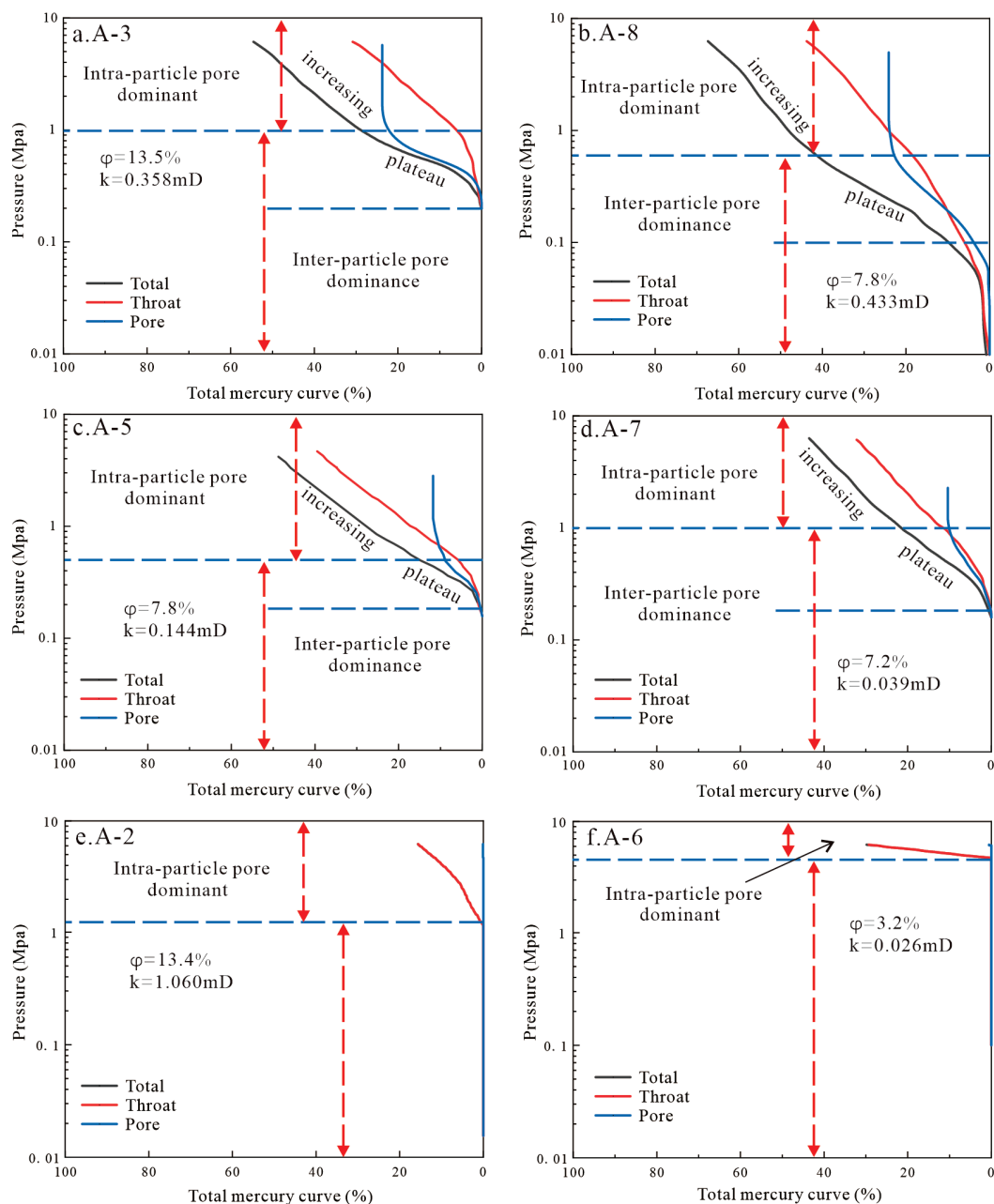


Figure 9. The Hg intrusion curves from CMI tests.

4.4. FE-SEM Observation and AMICS Analysis After WM Impregnation

The Wenchang Formation sandstone samples are predominantly composed of quartz (32–75%), feldspar (18–40%), and calcite (3–24%), which together account for over 90% of the mineral content. In addition, the clay minerals are primarily smectite mixed-layer (I/S), kaolinite, and chlorite, with chlorite being the most abundant (except for sample A-6, with an average proportion of approximately 66%). A high proportion of chlorite is a typical characteristic of low-permeability sandstone. According to the scanning electron microscopy (SEM) analysis results (Figures 10 and 11), the pore types developed in the reservoir of the study area can be classified into three categories: intergranular pores, intragranular pores, and intergranular–intragranular pores [23]. Among these, intergranular pores exhibit the highest permeability, followed by intergranular–intragranular pores, while intragranular pores have the lowest permeability.

In samples A-5 and A-6, Wood's metal primarily contacts minerals such as quartz, potassium feldspar, chlorite, and calcite, with permeabilities of 0.144 mD and 0.026 mD, respectively. The proportions of metal are 2.27% and 0.61%, respectively. The low permeability results in poor injectability of the metal, leading to limited accessibility and poor connectivity. Specifically, the A-5 sample mainly develops intragranular pores in illite, albite, and chlorite, while the A-6 sample primarily develops intragranular pores in calcite, albite, and chlorite.

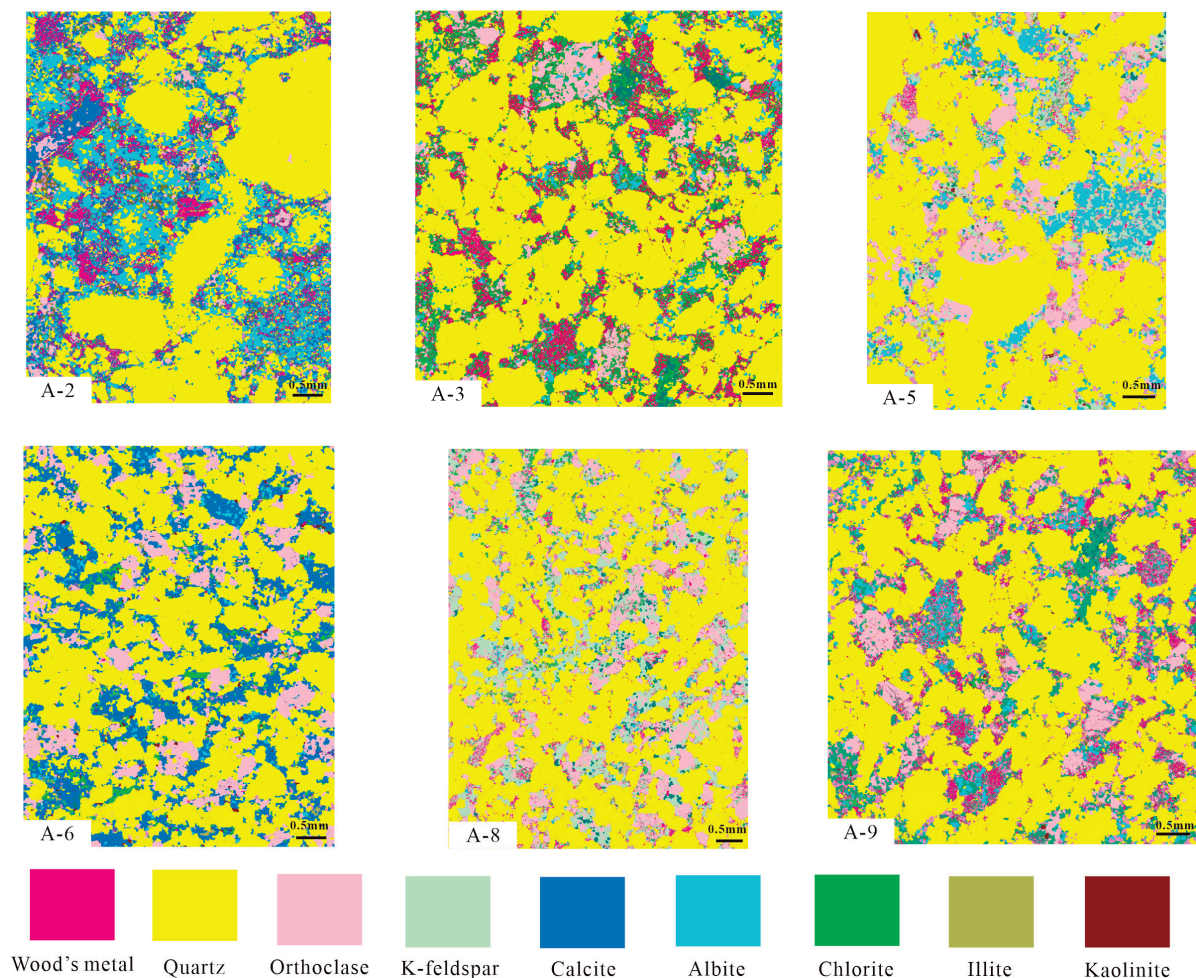


Figure 10. QEMSCAN results of six sandstone samples.

The pore system in low-permeability sandstone samples consists of intergranular pores, intragranular pores, and dissolution pores, with occasional microfractures. While intergranular pores exhibit the largest dimensions, they are relatively sparse and discontinuously distributed.

Ten SEM images of six samples following Wood's alloy injection experiments are presented, clearly demonstrating the metal infiltration patterns within the pore networks. In samples A-3, A-4, and A-10, extensive penetration of Wood's metal into intergranular pores was observed, confirming well-developed intergranular porosity. These interconnected pore networks serve as both primary hydrocarbon storage spaces and efficient migration pathways. In samples A-2, A-5, and A-1, the pore systems are predominantly composed of intragranular pores. Although these pores account for a substantial proportion of the total porosity, they contribute negligibly to the overall permeability of the samples [24].

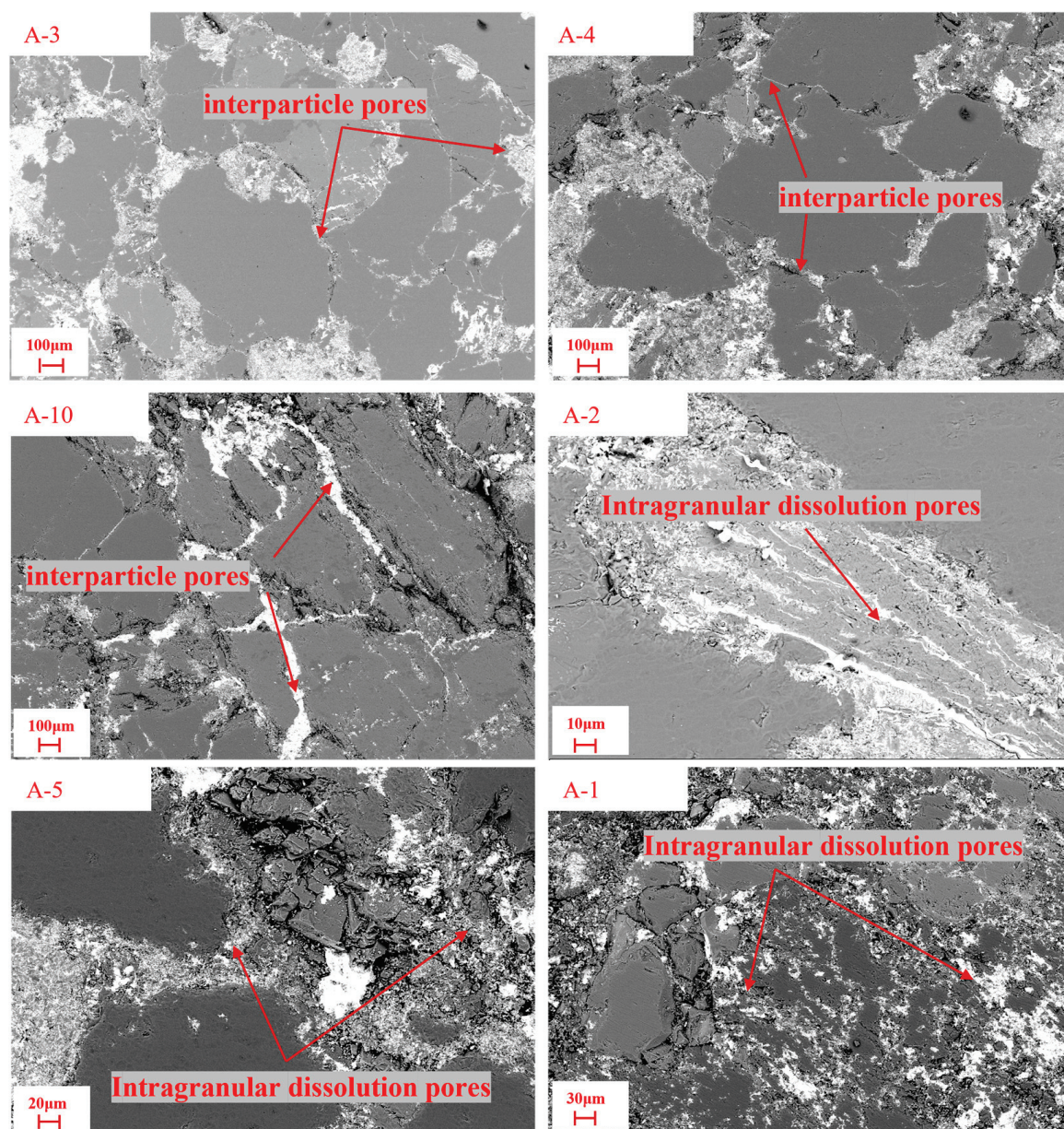


Figure 11. Pore type location and composition were observed by SEM. The planar observations of samples A-3, A-4, and A-10 were mainly intergranular pores. In samples A-2, A-5, and A-1, the planar observation is mainly intragranular pores.

5. Discussion

5.1. Petrological Characteristics and Reservoir Quality

The low-permeability sandstone reservoir in the Wenchang Formation of the Huizhou area exhibits significant heterogeneity in terms of porosity and permeability [25]. The wide range in porosity (3.19% to 14.09%) and permeability (0.026 mD to 1.060 mD) values, despite the similar depths of the samples, indicates complex pore structure development influenced by mineralogical composition [26]. This heterogeneity is typical of low-permeability sandstone reservoirs globally and presents challenges for effective hydrocarbon exploration and production.

The predominance of quartz (average 59.4 wt.%) establishes a relatively stable framework for the reservoir, while variable feldspar content (13–40 wt.%) suggests different degrees of diagenetic alteration. The inverse relationship between calcite and quartz con-

tent indicates that carbonate cementation significantly affects reservoir quality (Figure 12a), likely reducing primary porosity through pore-filling precipitation. The presence of barite exclusively in samples with lower quartz content suggests that mineral precipitation may be a porosity-reduction mechanism in specific intervals.

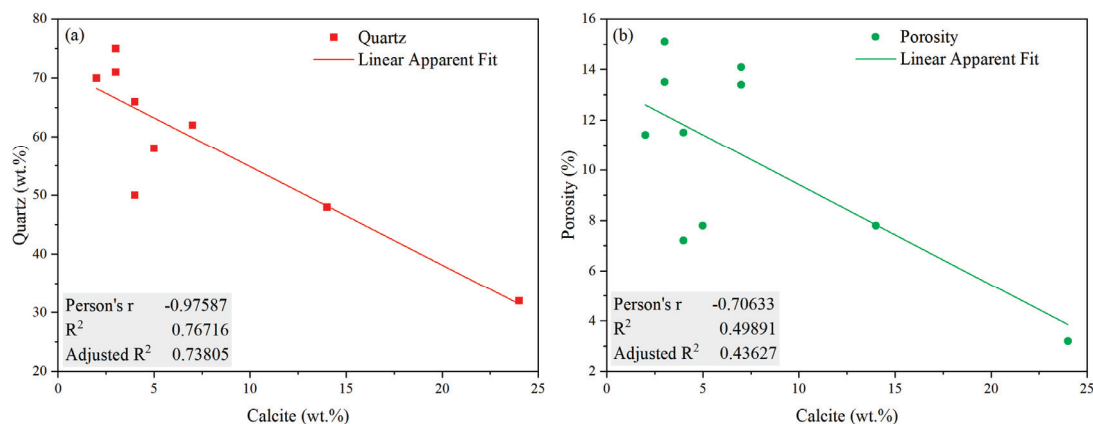


Figure 12. Calcite content vs. quartz content and porosity. There is a negative correlation between calcite and quartz content (a). There is a negative correlation between calcite and porosity (b). Overfilling of calcite reduces porosity.

The relatively low clay mineral content (average 5.3%) is somewhat unusual for low-permeability sandstone reservoirs (Figure 12b), which typically exhibit higher clay percentages. This suggests that pore-throat reduction in this reservoir may be more controlled by compaction and cementation rather than clay infiltration [27]. In addition, abundant calcite tends to occlude pores, exerting negative impacts on both the porosity and permeability of the reservoir. The lithological classification of primarily lithic arkose and feldspathic litharenite reflects the moderately mature nature of these sandstones, consistent with their tight-reservoir characteristics [28].

5.2. Pore Structure Characteristics

The MICP results provide critical insights into the pore-throat architecture of these sandstones. The systematically lower porosity values from MICP compared to helium porosity measurements confirm the presence of micropores below the detection limit of mercury intrusion, which can only access pore throats larger than 7.25 nm. This difference highlights the significance of micropores in contributing to the total storage capacity but not to the flow capacity [29].

The high maximum mercury saturation (average 89.9%) compared to conventional low-permeability reservoirs indicates better hydrocarbon storage capacity. However, the low mercury withdrawal efficiency (average 22.6%) reveals poor pore connectivity, which explains the low permeability values despite moderate porosity in some samples. This characteristic “storage-without-flow” phenomenon is typical of tight reservoirs and represents a significant challenge for production [30].

The variable displacement pressures (0.16 to 0.67 MPa) further demonstrate the heterogeneity of the pore network, with higher displacement pressures indicating smaller pore-throat diameters that require greater capillary pressure to overcome. The application of fractal dimension analysis provides a quantitative measure of pore complexity, with the identification of two inflection points in the fractal dimension curves suggesting distinct pore populations at different scales.

5.3. Pore Types and Their Contribution to Reservoir Quality

After we performed Wood's metal impregnation, the FE-SEM observations and AMICS analysis revealed three primary pore types: intergranular, intragranular, and combined intergranular–intragranular pores. The relative contribution of each pore type to overall permeability follows a clear hierarchy, with intergranular pores providing the highest permeability, followed by combined pores, and then intragranular pores showing the lowest permeability.

The samples with higher permeability (A-2 and A-8) demonstrate greater Wood's metal infiltration (8.77% and 3.92%, respectively), primarily filling intergranular spaces and dissolution pores. This confirms that connected intergranular porosity is the dominant contributor to flow capacity in these low-permeability sandstone. In contrast, samples dominated by intragranular porosity within minerals such as illite, albite, and chlorite (A-5 and A-6) show significantly lower permeability (0.144 mD and 0.026 mD) and limited metal infiltration (2.27% and 0.61%).

The mineral associations with different pore types provide additional insights into diagenetic controls on reservoir quality. The dissolution pores associated with calcite in sample A-2, which exhibits the highest permeability (1.06 mD), suggests that secondary dissolution of carbonate cement may enhance reservoir quality in certain intervals. Meanwhile, the dominant association of intragranular pores with clay minerals and feldspars in low-permeability samples points to the detrimental effects of mineral alteration on flow capacity.

6. Conclusions

This study presents a comprehensive investigation of pore structure characteristics in low-permeability sandstone reservoirs of the Eocene Wenchang Formation, Huizhou Sag, Pearl River Mouth Basin, Northern South China Sea, employing an integrated analytical approach by combining MICP, CMI, WM, SEM, XRD, and QEMSCAN.

The following conclusions were drawn from this study:

- (1) The Wenchang Formation exhibits a “storage-but-not-flow” profile characterized by moderate porosity (average 10.5%) and very low permeability (average 0.3706 mD). The high quartz content (average 59.4%) provides a stable framework, but variable diagenesis (feldspar dissolution with calcite cementation) has an important negative impact on reservoir quality.
- (2) Micropores (<7.25 nm) contribute significantly to storage capacity, with high MICP saturation (average 89.9%), but exhibit poor flow performance. Effective permeability depends primarily on connected intergranular pores and dissolution features, not isolated intragranular pores.
- (3) Understanding the link between pore-throat architecture (connectivity and size) and mineralogical composition (especially diagenetic minerals like calcite and feldspar) is crucial for predicting reservoir quality and planning production in this heterogeneous system.
- (4) Future exploration should prioritize intervals with enhanced intergranular porosity and dissolution features for optimal hydrocarbon recovery. Initial regression results, while suggestive, require cautious interpretation and larger datasets for robust statistical power.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the nature of this research.

Conflicts of Interest: Author Guanliang Zhang was employed by the China National Offshore Oil Corporation. Author Qibiao Zang was employed by the China National Offshore Oil Corporation Limited-Shenzhen. There maining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Article

Analysis of Progradational and Migratory Source-to-Sink Systems and Reservoir Characteristics in the Steep-Slope Zone of Wushi Sag, Beibuwan Basin, South China Sea

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Abstract: Predicting favorable reservoirs controlled by source-to-sink systems in rift basins is a current research focus. Using seismic, core, drilling, logging, and thin-section data, this paper systematically identifies fan types and their reservoir characteristics controlled by two boundary faults in the southern steep-slope zone of Wushi Sag, Beibuwan Basin, South China Sea. The analysis compares differences in (1) source–channel–margin–sink systems and (2) diagenetic facies, dividing the sink area into migratory and progradational fans. Results show that migratory fans are associated with denudation. Sediments migrate through wide, deep “V”-shaped valleys, forming fan deltas that are large in area but short in progradation. Lithology is dominated by fine sandstone with siltstone interbeds, reservoirs’ diagenetic evolution is weak, pores are mainly primary, and Type I–II reservoirs are developed. In contrast, progradational fans reflect weaker source area denudation, with sediments prograding through narrow, shallow “U”-shaped valleys. These form broom-shaped fan deltas that are small in area but long in progradation, with lithology dominated by fine sandstone interbedded with mudstone. Reservoirs show strong diagenetic evolution, well-developed secondary porosity, and Type II–III reservoirs. Reservoir prediction models indicate that high-quality migratory reservoirs are large, with excellent physical properties and oil-bearing capacity, mainly in fan stacking zones. High-quality progradational reservoirs are concentrated in the fan midsections, with strong cementation and secondary porosity. These findings provide a theoretical basis for reservoir prediction and oil and gas exploration in the southern steep-slope zone of Wushi Sag.

Keywords: Liushagang formation; migratory fan; progradational fan; sedimentary reservoir variability

1. Introduction

Since the fan delta sedimentary system was first proposed in the 1960s, it has drawn increasing research attention. A fan delta is a subaqueous fan-shaped sedimentary system characterized by a proximal source, coarse sediments, and rapid accumulation—features that distinguish it significantly from alluvial fans and normal deltas [1–4]. As studies advanced, the focus shifted from typical outcrops and sediment characteristics to sedimentary models. Over the past 30 years, fan delta research has moved toward microscale reservoirs studies [5–7]. Case studies such as the Copper River Fan Delta in Alaska led to

the proposal of the progradational sedimentary system [2,8–12], characterized by continuous progradation under stable accommodation space [13–16]. In contrast, studies of the Yallahs Fan Delta in Jamaica and fan deltas in the Tarim Basin [17–19] inspired the concept of the migratory sedimentary system, defined by frequent channel avulsion and lateral migration of sedimentary centers [20,21]. By integrating the developmental characteristics of both systems [22–29], this study aims to clarify the “source–channel–boundary–sink” relationships, diagenetic features, and controlling factors of the southern steep-slope zone, ultimately providing a framework for reservoir development models.

Beibuwan is located in the northwestern area of the South China Sea, spanning the administrative regions of Guangdong Province, Guangxi Zhuang Autonomous Region, and Hainan Province. Its geographical coordinates are 19°52.8' N, 107°49.0' E [30]. Regional uplift during the Mesozoic transformed the Beibuwan Basin into a faulted sedimentary basin during the Cenozoic [31,32]. After decades of exploration, Wushi Sag has become one of the basin's two major oil- and gas-rich depressions. Located in the south-central Beibuwan Basin, its existing oilfields are experiencing declining productivity, creating an urgent need for new exploration targets. Previous studies have clarified the sedimentary characteristics and systems of the southern steep-slope zone in the Eocene Liushagang Formation and confirmed the development of a fan delta system during the deposition of its second member [33,34]. However, zones along the hanging wall of No. 7 Fault System (Figure 1C) are variably affected by burial depth, sedimentary microfacies, and reservoir type. Consequently, significant uncertainties remain regarding the “source–channel–boundary–sink” characteristics and reservoir properties of sedimentary bodies with different morphologies. In particular, the controlling factors, spatial distribution, and development models of high-quality reservoirs are still poorly understood.

Fan delta sediments developed in the southern steep-slope zone during the middle stage of the second member of the Liushagang Formation. However, the morphology and type of fan deltas differ significantly between the eastern and western parts of this zone, resulting in corresponding reservoir differences. Using seismic, core, well log, and laboratory data, this study investigates the southern steep-slope zone of the Wushi Sag with three main objectives: (1) to analyze sedimentary differences between migratory and progradational fan bodies from four perspectives, i.e., provenance, transport channels, boundary conditions, and sink systems; (2) to characterize reservoir types and diagenetic evolution for both systems, predicting the distribution of high-quality reservoirs; (3) to integrate sedimentary and reservoir differences, providing a framework for predicting high-quality reservoir distribution.

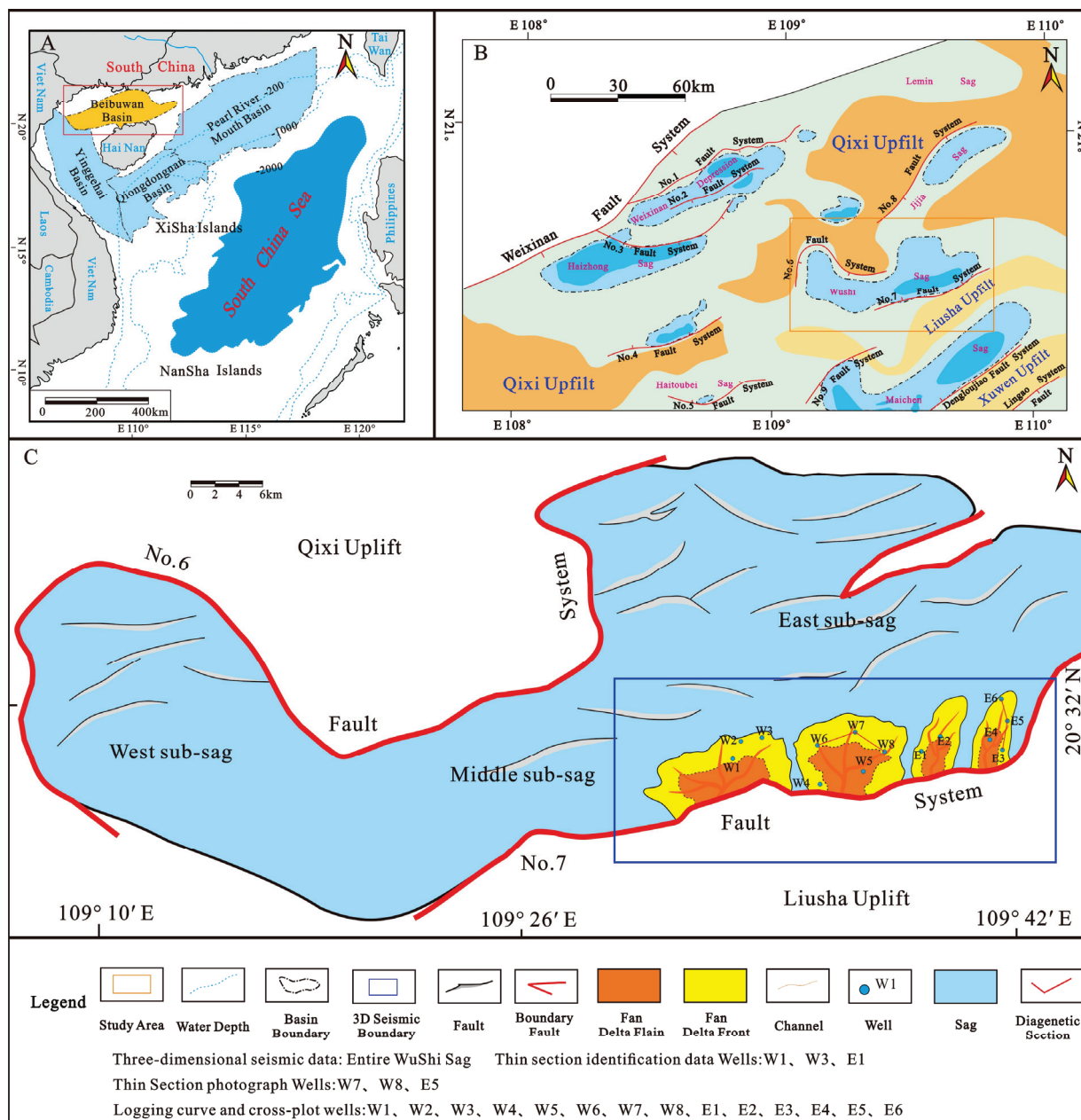


Figure 1. (A) Location map of Cenozoic-faulted basins in the northwestern South China Sea. (B) Tectonic unit division of the Beibuwan Basin (basin location shown in (A)). (C) Tectono-sedimentary units and sedimentary facies distribution of the southern steep-slope zone in the Wushi Sag (location shown in (B)).

2. Geological Setting

The Beibuwan Basin is a major oil-bearing basin in the northern South China Sea (Figure 1A), located south of Guangxi Zhuang Autonomous Region, north of Hainan Island, and adjacent to the Yinggehai Basin to the west. It covers approximately 3.9×10^4 km² and is divided into eight depressions and three uplifts (Figure 1B) [35]. The Wushi Sag is situated in the south-central Beibuwan Basin and spans about 1400 km² [36]. It is bordered by the Qixi Uplift to the northwest, the Jijia Sag and hinge zone of the Qixi Uplift to the northeast, and the Liusha Uplift to the south, forming a “surrounded by highlands” structural pattern. The Wushi Sag comprises three tectonic units: the East, Central, and West Sub-sag [37]. Oil shale in the East Sub-sag can serve as a high-quality source rock; tectono-sedimentary evolution within the sag has formed

favorable reservoir–caprock assemblages, and regional mudstone caprocks have created favorable conditions for oil and gas preservation [38]. Throughout the Cenozoic, the Wushi Sag experienced complex tectonic evolution with two major stages: (1) the Paleogene rifting stage (Paleogene Changliu to Oligocene Weizhou formations), characterized by intense faulting, controlling basin development, and (2) the Neogene depression stage (Oligocene Weizhou to Pliocene Wanglougang formations), marked by weakened faulting and the controlled development of sedimentation [32,39,40]. Faulting is widespread, with the No. 6 Fault System along the northern margin and the No. 7 Fault System along the southern margin (Figure 1C).

The Wushi Sag preserves a complete Cenozoic stratigraphic sequence, with a residual thickness of up to 6700 m, including continental Paleogene strata and marine Neogene strata. From bottom to top, the Paleogene comprises the Changliu, Liushagang, and Weizhou Formations, dominated by deltaic, sublacustrine fan, and lacustrine facies [41,42]. The Changliu Formation (65.5–55.8 Ma) consists mainly of conglomerate, pebbly sandstone, silty mudstone, and mudstone, representing alluvial–fluvial facies. The Liushagang Formation (55.8–35 Ma)—the focus of this study—was deposited during the early rifting stage and is ~2000 m thick [39,40]. Sequence stratigraphic analysis divides it into three members: (1) The third member has a “coarse-bottom, fine-top” lithology, with interbedded brown-gray mudstone and gray sandstone. (2) The second member has a “fine-coarse-fine” lithology consisting of (a) basal dark-brown oil shale of semi-deep to deep lacustrine facies, (b) deltaic, fan-deltaic, and sublacustrine fan deposits from the lake regression phase [37,43], and (c) gray-black oil shale and shale of deep lacustrine facies at the top. (3) The first member has a “coarse-bottom, fine-top” pattern, with interbedded gray mudstone and sandstone, containing braided river delta deposits [39,44,45]. The Weizhou Formation (35–23 Ma) is up to 3000 m thick, composed mainly of conglomerate, sandstone, and interbedded sandstone–mudstone, with meandering river delta deposits. The study area lies on the hanging wall of the No. 7 Fault System in the southern central sub-depression. During the deposition of the second member of the Liushagang Formation, fan delta systems derived from the Liusha Uplift developed in this area (Figure 2).

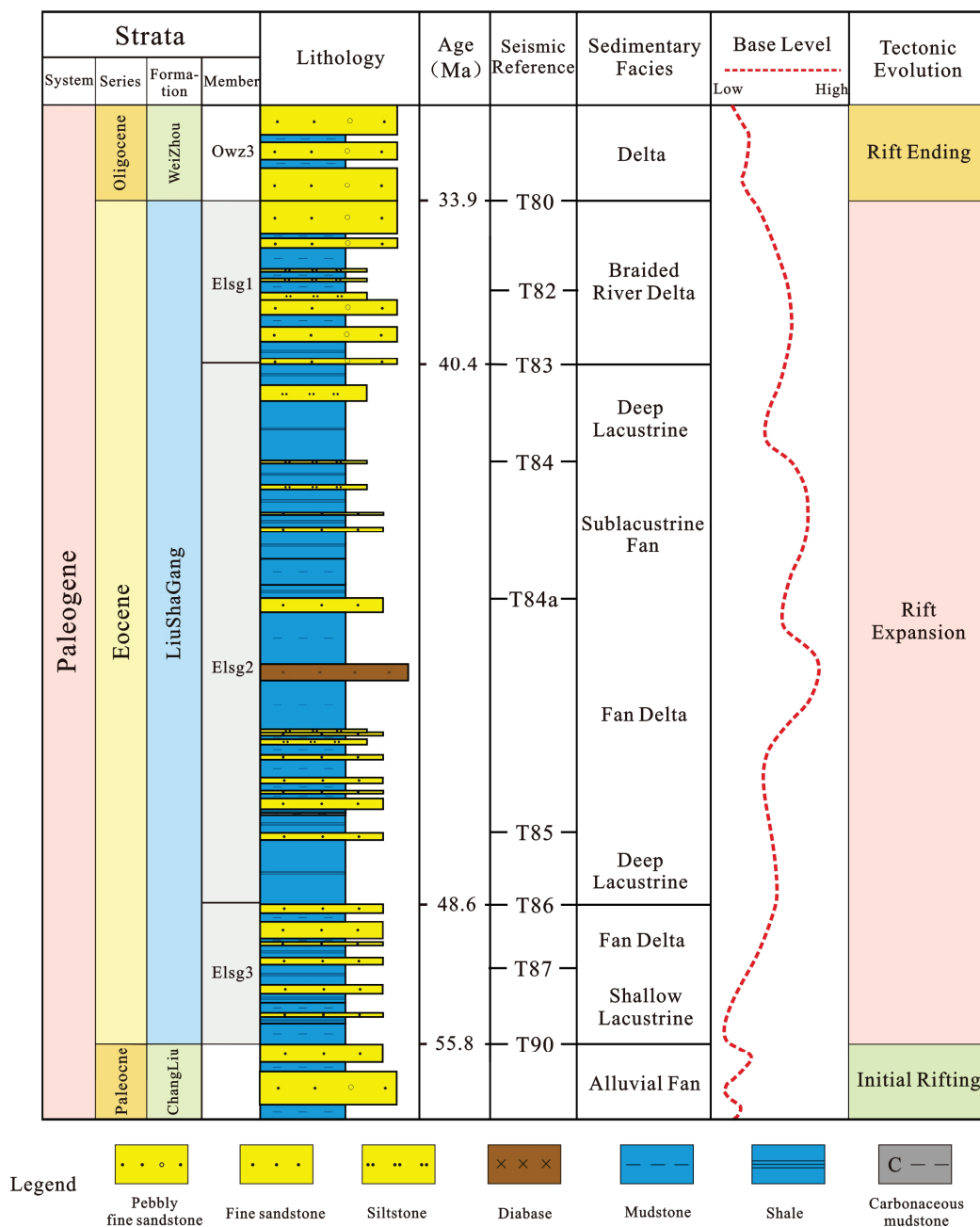


Figure 2. Columnar section of the Paleogene stratigraphic and tectonic evolution of the Wushi Sag, Beibuwan Basin (modified from [46]).

3. Materials and Methods

Extensive data, including core samples, 3D seismic surveys, well logs, thin-section analyses, and laboratory tests, were used to investigate the sedimentary characteristics and reservoir differences of the two fan types in the southern steep-slope zone of the Wushi Sag. All data were provided by the Zhanjiang Branch of the China National Offshore Oil (Zhanjiang, China).

The 3D seismic data cover ~300 km² of the southern Wushi Sag with a dominant frequency of 30–35 Hz. Seismic interpretation of the two fan types was performed using GeoFrame, focusing on sequence stratigraphic analysis, RMS attribute extraction, paleogeomorphic restoration, drainage system characterization, and fan boundary identification.

Paleogeomorphic restoration used the “three zones and five steps” method, identifying depositional and transgressive denudation zones on seismic profiles. The

five steps included (1) tectonic–sedimentary unit division, (2) differential subsidence correction, (3) denudation restoration, (4) sedimentary paleogeomorphic reconstruction, and (5) paleogeomorphology-based sedimentary unit division [47,48]. Following restoration, drainage systems were characterized based on topographical variations. Typical seismic profiles were analyzed for fault characteristics (angle, morphology), reflection patterns (progradational geometry, amplitude, frequency), and RMS attributes to interpret the “source–channel–boundary–sink” system of the fans.

The study area included 14 wells (W1–W8, E1–E6). Lithologic logging was used to identify lithologies and sedimentary microfacies. Well logs—gamma ray (GR), acoustic travel time (AC), compensated neutron (CNC), density (DEN), and resistivity (RD)—were applied to differentiate sandstone and mudstone intervals, and cross-plot analysis supported diagenetic facies identification. Oil testing was performed to access hydrocarbon-bearing properties clarifying the macro-sedimentary characteristics of each fan type.

Thin-section petrography was conducted on six wells (W1, W3, W7, W8, E3, E5) using sidewall cores, with the results summarized in technical reports and micrographs to compare petrology and diagenesis between the fan types. Physical property analysis of eight wells (W1, W3, W4, W7, W8, E2, E3, E5) measured porosity and permeability to evaluate reservoir quality differences.

Guided by sedimentary microfacies interpretation and logging cross-plots, diagenetic facies were classified and tied to wells. The distribution of high-quality reservoirs was determined by integrating sedimentary microfacies and diagenetic facies data. Combining seismic, well, and core data with principles of sequence stratigraphy, sedimentology, and reservoir geology, this study summarizes the macro-sedimentary and micro-reservoir characteristics of the two fan, clarifies their control over reservoir quality, and proposes predictive models for reservoir development.

4. Results and Interpretations

4.1. Source-to-Sink Systems

4.1.1. Source Area Characteristics

Using 3D seismic data and paleo-denudation analysis, we reconstructed the geomorphology and drainage systems of the Liusha Uplift in the southern study area. The results show distinct characteristics for the two fan types (Figure 3). (1) Migratory fans: their provenance areas exhibit intense denudation, cover large areas, and provide ample sediment supply. Their drainage systems are interconnected, forming composite “linear provenance” systems that develop distal migratory source-to-sink systems. (2) Progradational fans: their provenance areas show weak denudation, are smaller, and have limited sediment supply. Their drainage systems are isolated, forming single “point provenance” systems that develop proximal progradational source-to-sink systems.

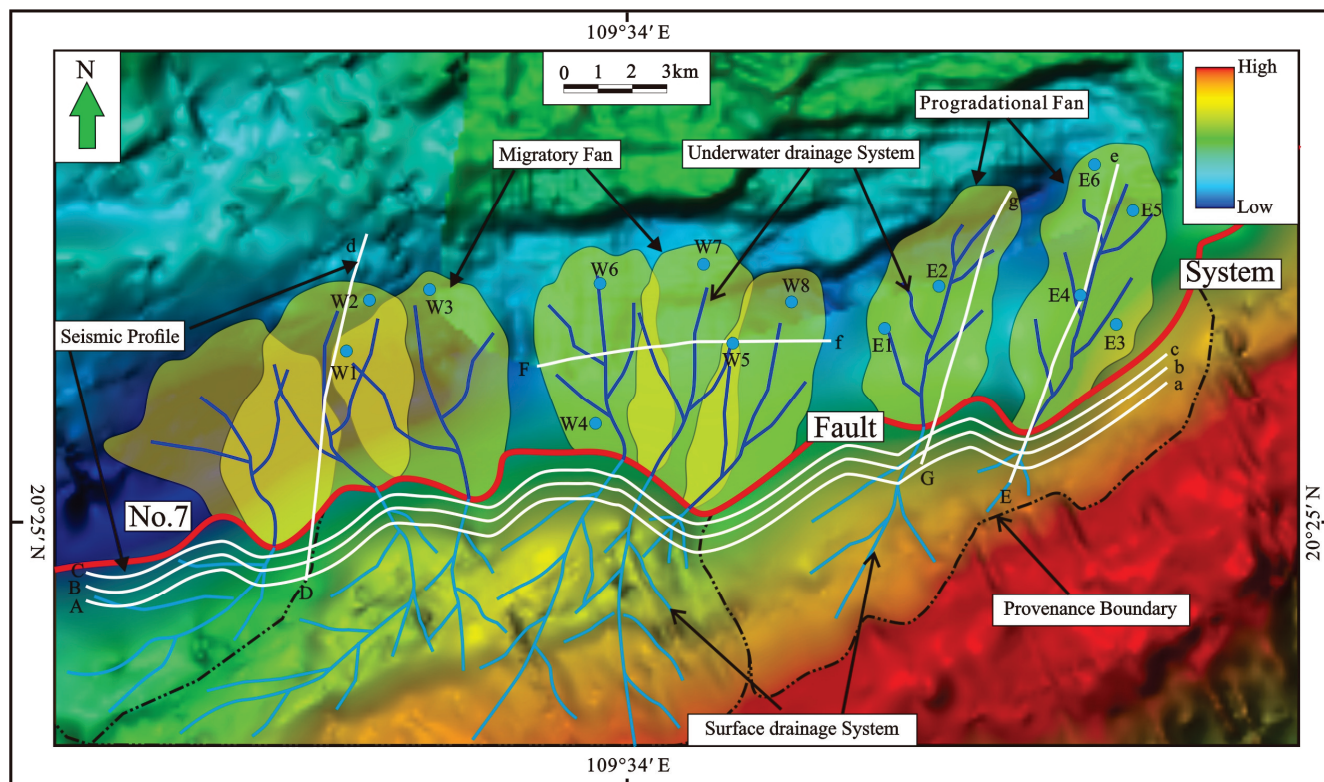


Figure 3. Paleogeomorphology, drainage system characteristics of the provenance area, and distribution of sedimentary fan bodies in the southern steep-slope zone of the Wushi Sag, Beibuwan Basin (Aa, Bb, Cc, Dd, Ee, Ff and Gg indicate seismic profiles).

4.1.2. Channel Characteristics

Analysis of three seismic profiles perpendicular to the provenance of the Liusha Uplift in the southern steep-slope zone of the Wushi Sag reveals that transport is dominated by four fault-controlled channels (V1-1, V1-2, V2-1, V2-2). V1-1 and V1-2 correspond to migratory sedimentary systems, while V2-1 and V2-2 correspond to progradational systems. Qualitative and quantitative analysis of channel shape, width, and depth highlights the differences in transport characteristics between the two systems.

Channel V1-1 maintains a “V” shape throughout, averaging 3860 m in width and 340 ms in depth, indicating strong erosional capacity. Channel V2-2 is consistently a “U” shape, averaging 2875 m in width and 250 ms in depth, reflecting weaker erosion. Channels V1-2 and V2-1 are single channels in the early stage but bifurcate later. V1-2 transitions from “U”- to “V”-shaped, with an average width of 5430 m and depth of 770 ms, indicating strong erosion. V2-1 remains “U”-shaped, averaging 3600 m in width and 310 ms in depth, suggesting relatively weak erosional capacity (Figure 4).

In summary, migratory fan channels are wide, deep, strongly erosive, and “V”-shaped, with ample sediment supply, whereas progradational fan channels are narrower, shallower, weakly erosive, and “U”-shaped, with limited sediment supply.

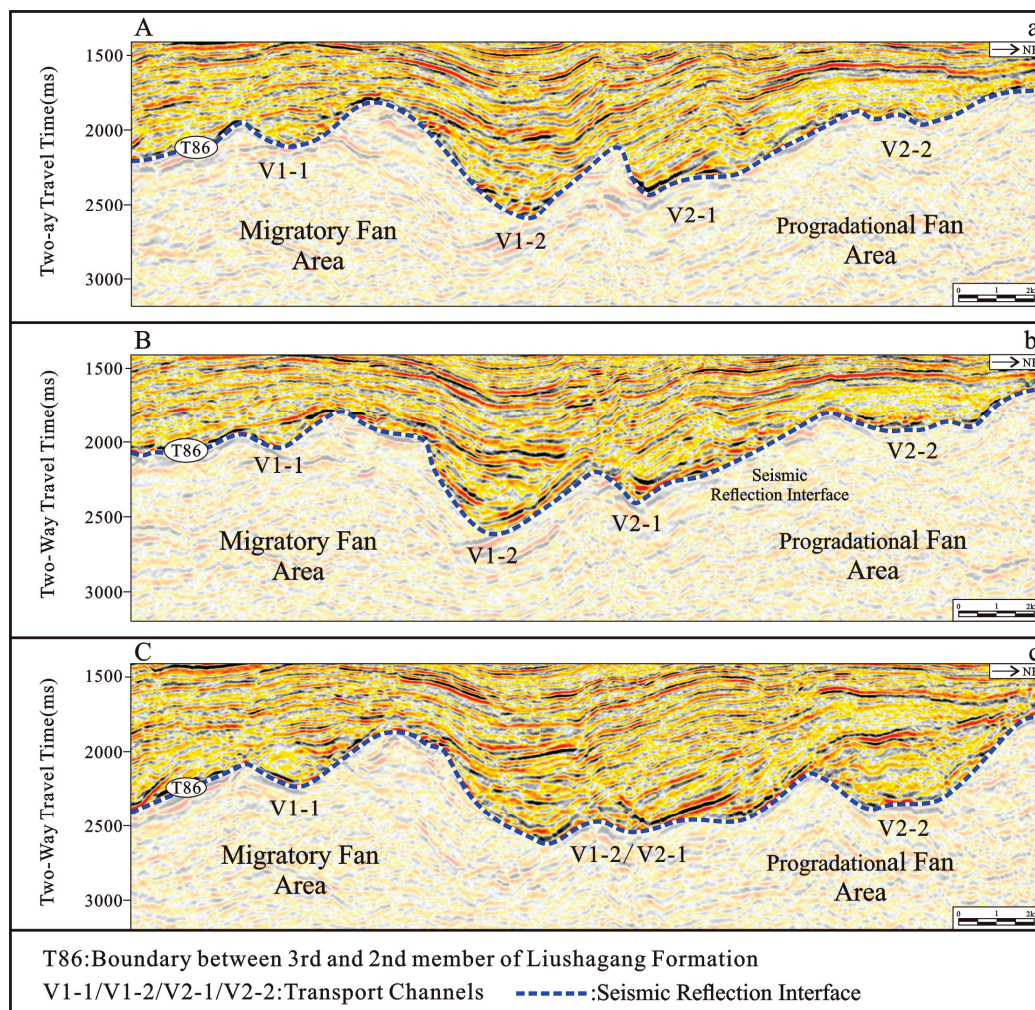


Figure 4. Seismic profiles (SW–NE) showing channel evolution in Aa, Bb, and Cc of the southern steep-slope zone, Wushi Sag, Beibuwan Basin (profile locations shown in Figure 3).

4.1.3. Boundary Characteristics

The No. 7 Fault System is the primary sedimentary boundary in the southern steep-slope zone of the Wushi Sag. It strikes NEE, extends ~45 km, and dips NNW, with its dip angle decreasing from west to east. Its geometry transitions from listric in the west to fault benches and multi-level Y-shaped patterns eastward. Fault activity gradually weakened during the deposition of the second member of the Liushagang Formation [49,50].

This paper characterizes the fault boundary based on its development and transfer zone morphology. From the early to late stages of the second member of the Liushagang Formation, fault activity in the west weakened, with the maximum fault throw decreasing from 1400 m to 500 m (Figure 5). Seismic reflections show a low-angle upper fault bench overlying a high-angle boundary fault, forming a boundary that is gentle above and steep below (Figure 6). In contrast, fault activity in the east is strengthened, with the maximum throw increasing from 500 m to 800 m (Figure 5). Here, the upper section is controlled by a high fault, while the lower section shows a progressively shallower dip as the fault dies out, producing a steep-above, gentle-below boundary (Figure 6). These contrasting fault patterns control the internal sedimentary architecture of the basin.

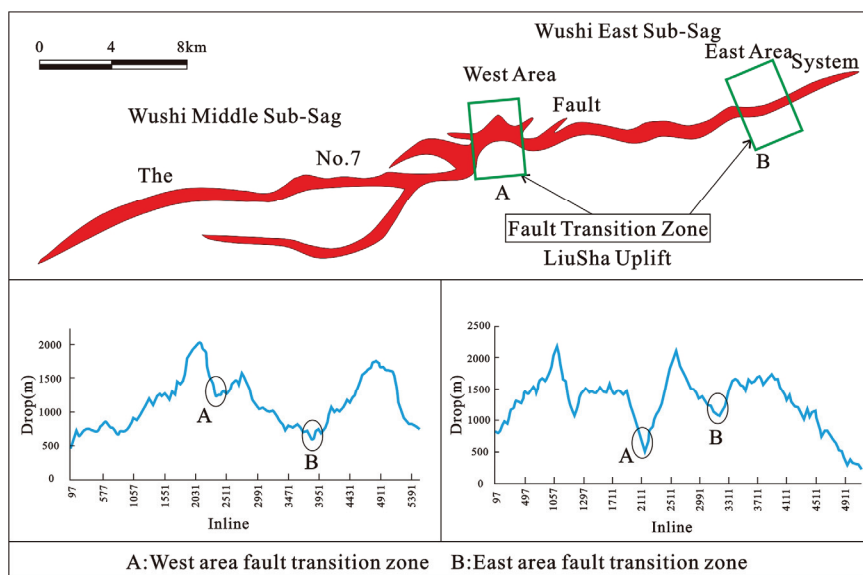


Figure 5. Transfer zone location and fault throw of the No. 7 Fault System, Wushi Sag, Beibuwan Basin.

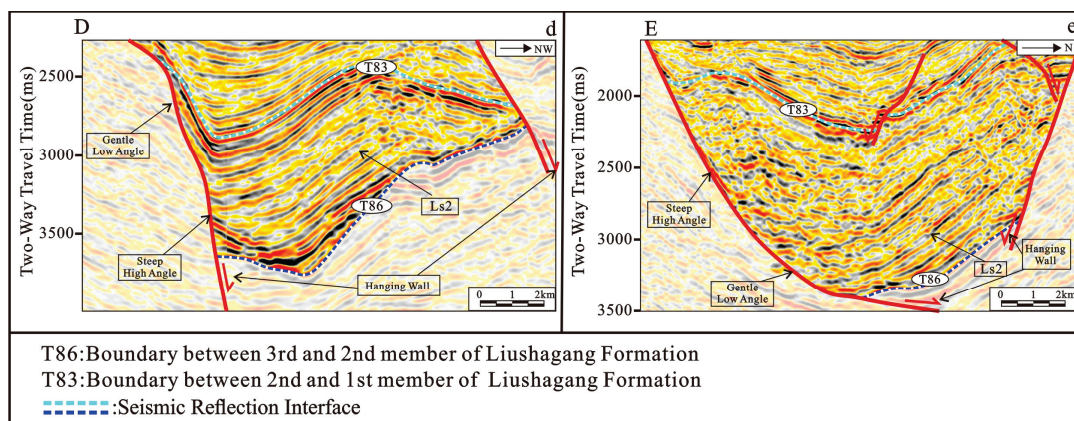


Figure 6. Seismic profiles Dd (SE–NW) and Ee (S–N) showing fault morphology in the southern steep-slope zone of the WuShi Sag, Beibuwan Basin (profile locations shown in Figure 3).

4.1.4. Depositional System Characteristics

Differences between the two depositional systems are evident in seismic facies, planar attributes, and lithologic associations. For migratory fans, three development stages are identifiable in profiles perpendicular to the source. Seismic reflections show left-right migration, with medium-to-strong amplitudes and moderately continuous parallel reflections (Figure 7). Lithology is dominated by fine sandstone and argillaceous siltstone interbedded calcite with mudstone, containing both oil and water-bearing layers (Figure 8B). High RMS seismic attribute values occur in the fan center (Figure 8A). In map view, successive fans overlap laterally, forming a broad, fan-shaped delta with a relatively large areal extend (Figure 8C).

For progradational fans, two development stages are identifiable in profiles perpendicular to the source. Seismic reflections show successive forward progradation with medium-to-strong amplitudes and moderately continuous progradational reflections (Figure 7). Lithology is dominated by mudstone interbedded with fine sandstone and silty mudstone (Figure 8E). High RMS seismic attribute values occur at the fan front (Figure 8D). In map view, fans of successive stages show continuous progradation, forming a relatively small, broom-shaped delta (Figure 8C).

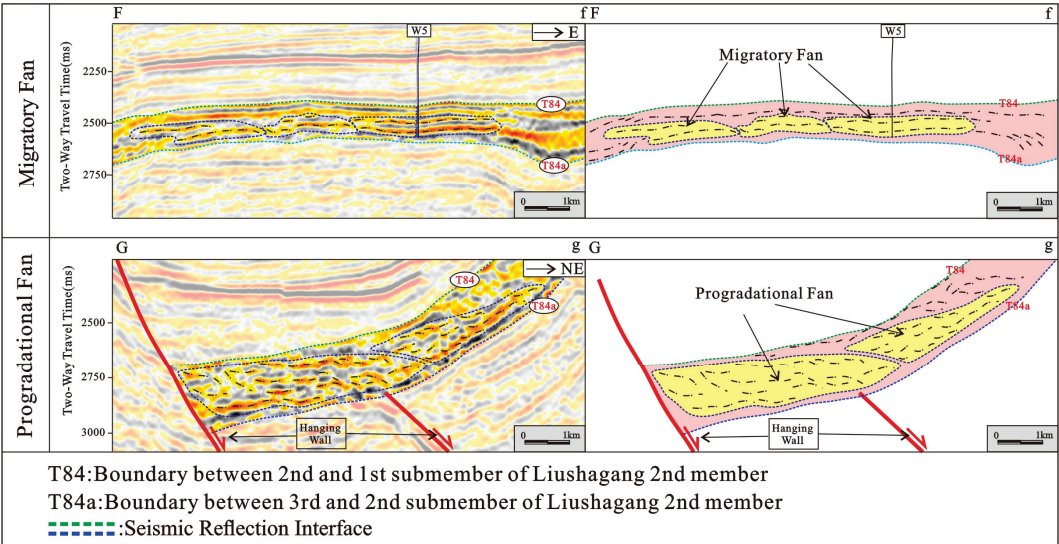


Figure 7. Seismic profiles Ff (W–E) and Gg (SW–NE) showing seismic reflection characteristics of the sedimentary system in the southern steep-slope zone of the WuShi Sag, Beibuwan Basin (profile locations shown in Figure 3).

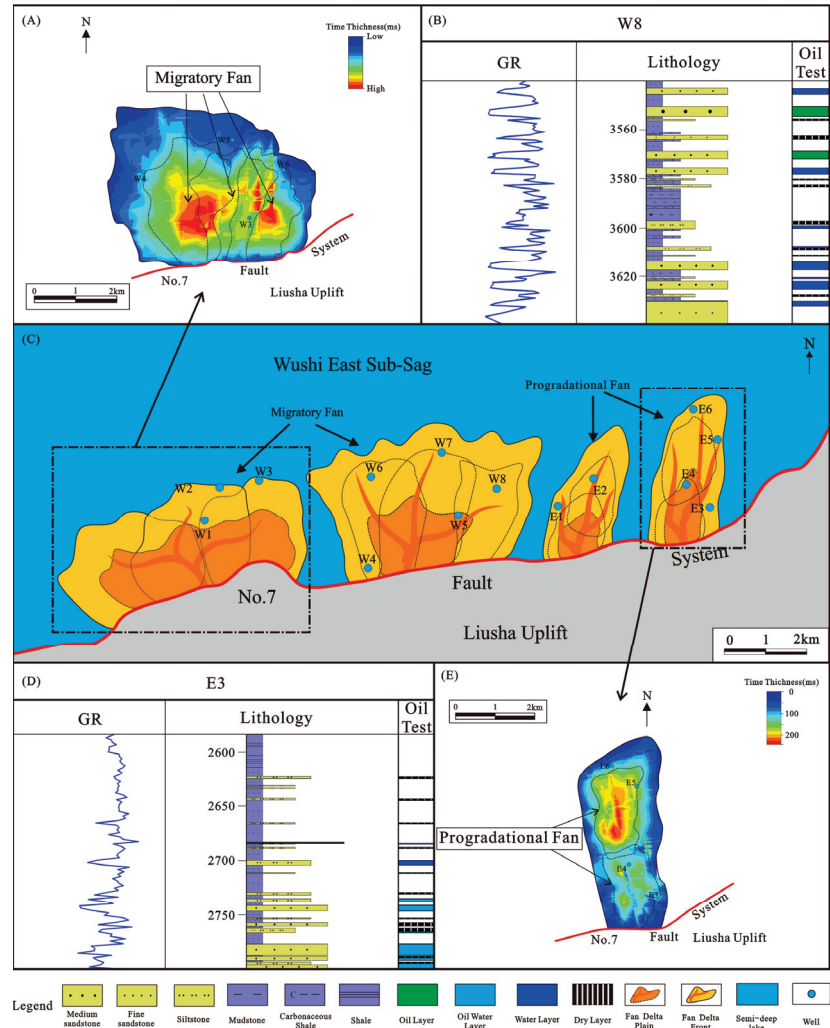


Figure 8. (A,E) RMS attributes, (B,D) Lithology, and (C) sedimentary facies distribution of migratory and progradational fan deltas in the southern steep-slope zone of the Wushi Sag, Beibuwan Basin (well locations shown in Figure 1C).

4.2. Reservoir Characteristics

4.2.1. Reservoir Petrological Characteristics

Thin-section and physical property analyses were performed on sidewall core samples from eight drill holes. Grain composition and interstitial materials were statistically evaluated, using triangular diagrams and bar charts. Results show that migratory fans are dominated by feldspathic litharenites and litharenites, with the interstitial materials mainly comprising an argillaceous matrix (Table 1, Figure 9A). Progradational fans are dominated by litharenites, feldspathic litharenites, and lithic quartz arenites, with the interstitial materials mainly composed of an argillaceous matrix and carbonates (Table 1, Figure 9B).

Table 1. Summary of clastic particles and interstitial materials in migratory and progradational fans of the Wushi Sag, Beibuwan Basin.

Clastic Particles, Interstitial Materials	Migratory Fan		Progradational Fan	
	Range	Average	Range	Average
Quartz/%	16.9–67.8	54.2	8.2–82.9	65.4
Feldspar/%	8.6–20.1	12.4	4.2–10.3	7.7
Lithic/%	22.8–72.3	33.4	10.5–81.5	26.9
Argillaceous matrix/%	1.0–10.0	3.5	0.5–18.0	3.5
Carbonate cements/%	0.5–7.5	2.2	0.5–20.0	3.6
Clay minerals/%	0.5–1.6	0.9	0.5–2.0	0.6
Siliceous cements/%	0.5–2.0	0.5	0.2–0.8	0.5
Bitumen/%	0.0–2.0	1.5	0.0–2.0	1.4

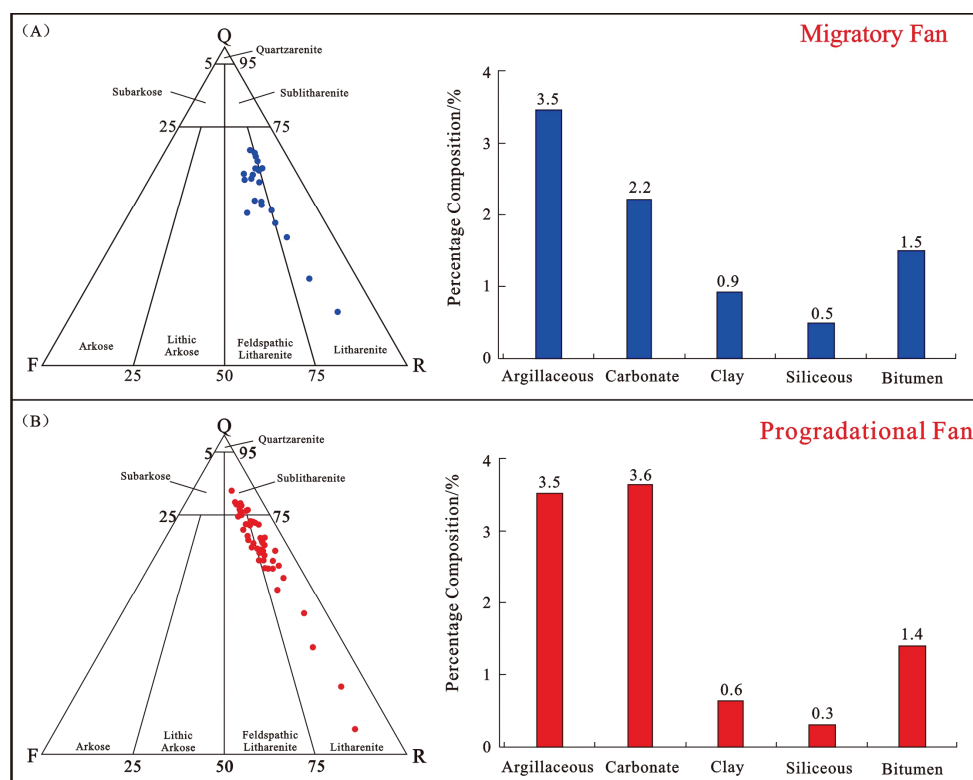


Figure 9. Lithic triangular diagrams and interstitial material bar charts of migratory fans (A) and progradational fans (B) in the Wushi Sag, Beibuwan Basin (Q, quartz; F, feldspar; R, rock fragments; modified from [51]).

4.2.2. Reservoir Diagenesis

This study focuses on differences between the two fan types in terms of compaction, cementation, and dissolution, to guide subsequent diagenetic facies analysis.

Migratory fan bodies, formed by overlapping sedimentary units, have greater thickness, lower mud-to-sand ratios, and relatively weak compaction, characterized mainly by point–line grain contacts (Figure 10A). Dissolution is intense, producing well-developed secondary pores (Figure 10B). Carbonate material from altered lithic fragments rarely forms carbonate cement within sand bodies; at greater burial depths, argillaceous cementation predominates (Figure 10C).

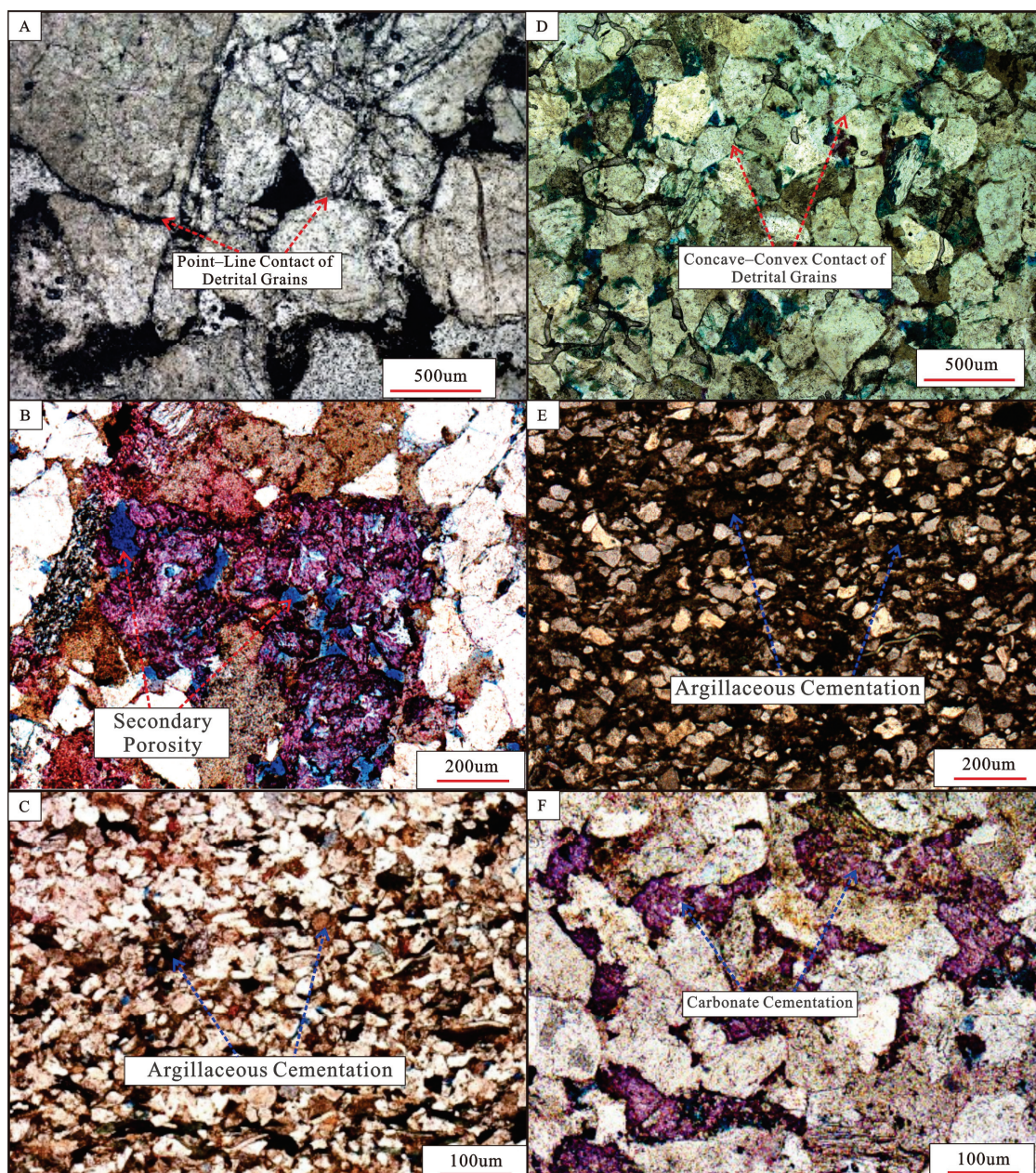


Figure 10. (A) W8 at 3081.5 m: particles in line contact. (B) W8 at 3081.5 m: coarse-grained particles with dissolution pores, porosity 20.6%. (C) W8 at 3101.8 m: fine-grained particles with high argillaceous content, compacted and orientated, pores undeveloped. (D) E5 at 3468.5 m: particles in concavo-convex contact. (E) E5 at 3391 m: high argillaceous content with developed argillaceous strips, strong compaction, porosity 5.5%. (F) E5 at 3603.2 m: strong calcite cementation, pores undeveloped, porosity 7.5%.

Progradational fan bodies, formed by continuous sediment progradation, have relatively thin sand bodies, high mud-to-sand ratios, and well-developed interbedded layers. Particle compaction is strong, with concavo-convex grain contacts (Figure 10D). Dissolution is weak, and secondary pores are scarce. Carbonate materials from altered carbonate lithic fragments readily form carbonate cement within the sand bodies, resulting in reservoirs controlled by both argillaceous and carbonate cementation (Figure 10E,F).

4.2.3. Reservoir Physical Property Characteristics

Statistical analysis of reservoir properties shows significant differences in porosity and permeability between migratory and progradational fans in the southern steep-slope zone of the Wushi Sag. Overall, migratory fans exhibit higher average porosity and permeability.

1. Migratory Fans

Porosity: 5.7–21.0%, (avg. 13.28%).

Permeability: 0.06–288 mD, (avg. 8.38 mD) (Figure 11).

2. Progradational Fans

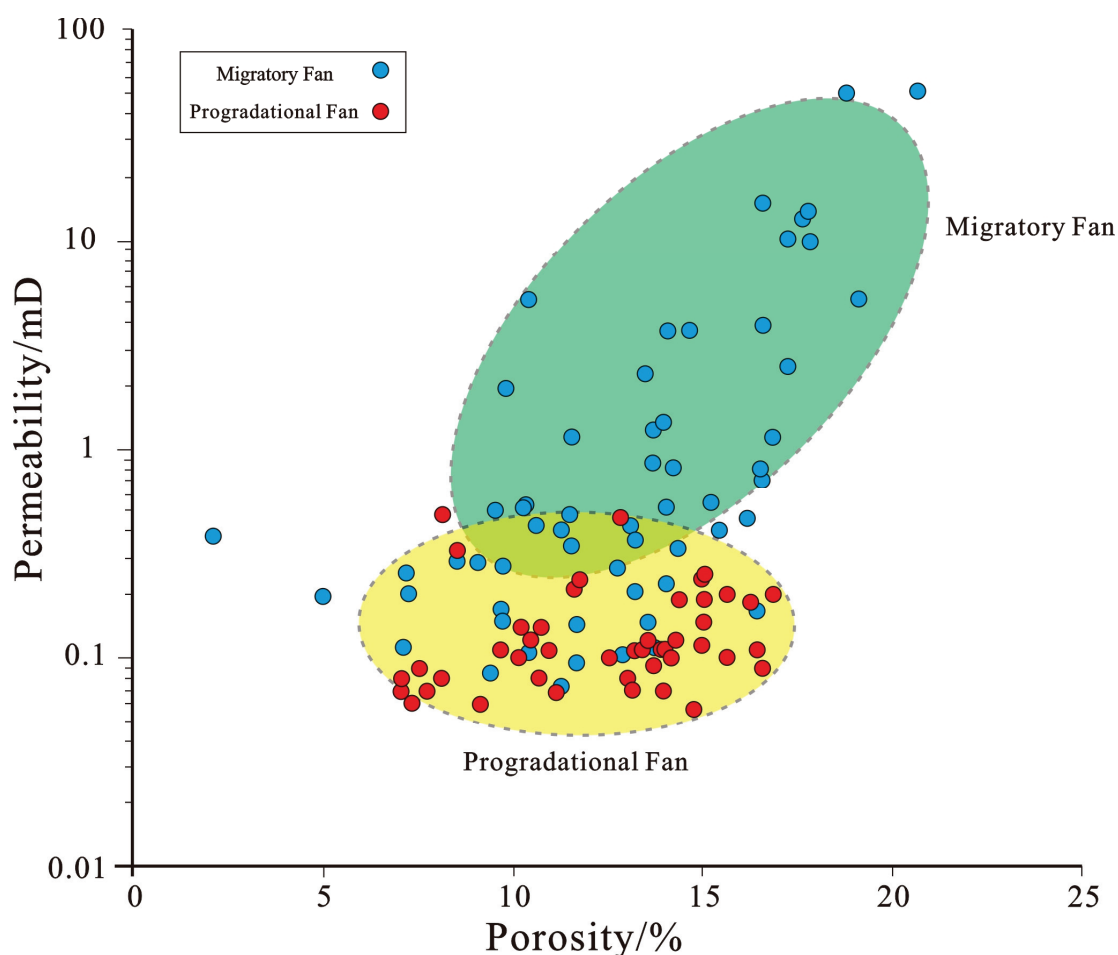


Figure 11. Cross-plot of porosity and permeability for progradational fans and migratory fans in the southern steep-slope zone of the Wushi Sag, Beibuwan Basin.

Porosity: 2.1–20.6%, (avg. 12.86%).

Permeability: 0.07–51.96 mD, (avg. 3.58 mD) (Figure 11).

5. Discussion

By comparing the two fan types in the southern steep-slope zone of the Wushi Sag, the controlling factors and reservoir development models of progradational and migratory systems were summarized, and favorable exploration directions for both systems were identified.

5.1. Controlling Factors

Through a comparison of the source-to-sink and reservoir differences between migratory and progradational fans in the Wushi Sag, it is considered that sedimentary factors (macroscopic) and lithofacies factors (microscopic) jointly control the differences between the two types of fan.

5.1.1. Sedimentary Factors

Sedimentary factors underlie the differences between the two fan types, controlling their development characteristics and scales. In the southern steep-slope zone of the Wushi Sag, fan development is influenced by a major high-angle boundary fault. Distinct tectonic–geomorphic settings produce different “source–channel–boundary–sink” parameters, which determine the characteristics of the resulting sedimentary bodies. Comprehensive analysis of these parameters clarifies the tectonic–geomorphic–sedimentary coupling patterns.

Within the source-to-sink system, sink areas shaped by boundary fault patterns are classified as migratory and progradational fans. Migratory fan source areas experience strong erosion; weathered clastics, transported over long distances by stable drainage systems, follow a “gentle then steep” valley profile, migrate laterally, and are deposited in the sink area as fan delta bodies. In contrast, progradational fan source areas experience weaker erosion; clastics pass through a “steep then gentle” valley profile, prograde forward under accommodation space constraints, and form broom-shaped fan delta bodies (Table 2).

Table 2. Sedimentary types of migratory and progradation fans in the southern steep-slope zone of the WuShi Sag, Beibuwan Basin.

Sedimentary Type	Source			Valley			Fault		Sink		
	Drainage Type	Extend/km	Area/km ²	Shape	Width/m	Depth/ms	Type	Fault Angle	Shape	Thickness/m	Deposition Area/m ²
Migratory fan	Composite drainage	8	28.69	V	3860	340	Steep-slope	Low to high	Fan-shaped	332	38.587
		9.5	98.67		5430	770				309	42.16
Progradational fan	Single drainage	7	23.57	U	3600	310	Steep-slope	High to low	Broom-shaped	258	24.687
		2.7	5.26		2875	250				263	18.21

5.1.2. Diagenetic Facies Factors

Lithofacies factors are key in microscopically controlling reservoir quality and are primarily expressed through differences in diagenetic facies. Analyzing the diagenetic facies of migratory sedimentary systems helps clarify the microscopic distinctions between the two sedimentary system types.

1. Diagenetic facies types

Based on thin-section analysis, well log characteristics, and cross-plots, four diagenetic facies types were identified using two complimentary approaches:

The diagenetic facies are classified using the following two methods:

① Thin-section observations and quantitative statistics:

Type I: Medium compaction, weak cementation, strong dissolution, well-developed pores, porosity > 15%;

Type II: Medium compaction with clay mineral cementation medium, moderate dissolution, porosity 10–15%;

Type III: Strong compaction with argillaceous filling; matrix micropores dominate, poor connectivity, porosity 5–10%;

Type IV: Strong compaction with carbonate cementation and weak dissolution, very few pores, poor connectivity, porosity < 5%.

② Logging curves and cross plots (AC, CNC, DEN, RD) (Table 3):

Table 3. Typical logging curves of reservoir diagenetic facies.

Diagenetic Facies Type	AC/ ($\mu\text{m/s}$)	CNC/ (v/v)	DEN/ (g/m^3)	RD/ (Ω/m)
Type I diagenetic facies: medium compaction, weak cementation, strong dissolution	95–120	35–39	2.0–2.3	0–10
Type II diagenetic facies: medium compaction, clay cementation, moderate dissolution	70–90	16–20	2.2–2.4	10–30
Type III diagenetic facies: strong compaction with argillaceous filling	60–70	9–13	2.5–2.7	30–55
Type IV diagenetic facies: strong compaction with carbonate cementation, weak dissolution	65–80	10–15	2.3–2.5	20–35

Type I: Medium compaction, weak cementation, strong dissolution, low RD/DEN, high CNC/AC;

Type II: Medium compaction, clay cementation, moderate dissolution, intermediate RD, DEN, CNC, and AC values;

Type III: Strong compaction with argillaceous filling, high RD/DEN, low CNC/AC;

Type IV: Strong compaction with carbonate cementation, weak dissolution, high RD, medium–high DEN, low CNC and AC values.

2. Diagenetic facies in well-tie profiles

Well-tie profile analysis shows that in stacked migratory fan bodies, Type I and II facies dominate the middle section, while Types III and IV occur at the margins. With increasing depth, facies transition progressively from Types I–II to Types III–IV (Figure 12).

In progradational fan bodies, Type I facies (medium compaction, weak cementation) occur only in small amounts at the fan front, while Types III (strong compaction with argillaceous filling) and IV (strong compaction with carbonate cementation) are predominant. With increasing depth, facies transition from Type II to Types III–IV (Figure 13).

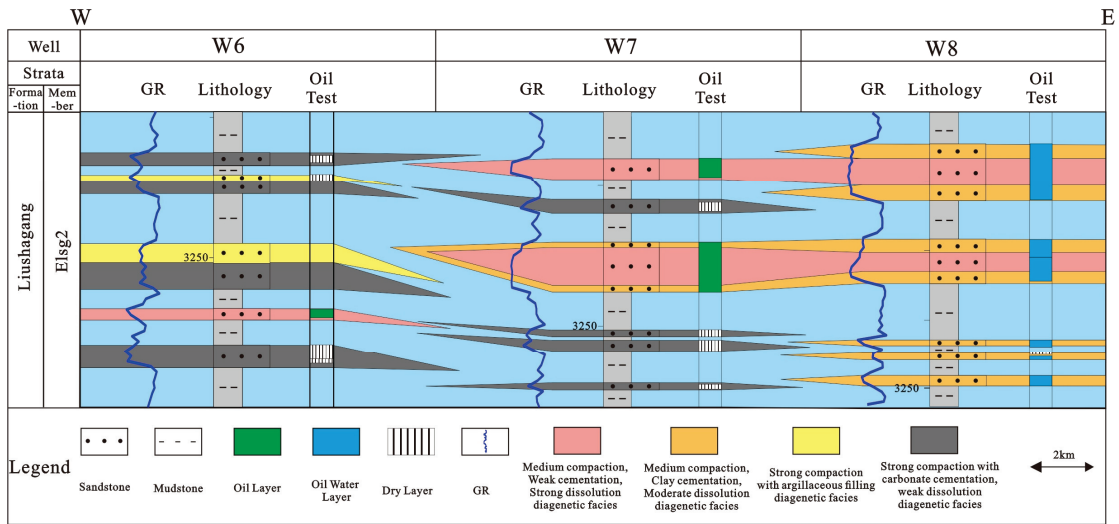


Figure 12. Cross-well diagenetic facies profile (wells W6–W8) for migratory fans in the Wushi Sag, Beibuwan Basin (section location shown in Figure 1).

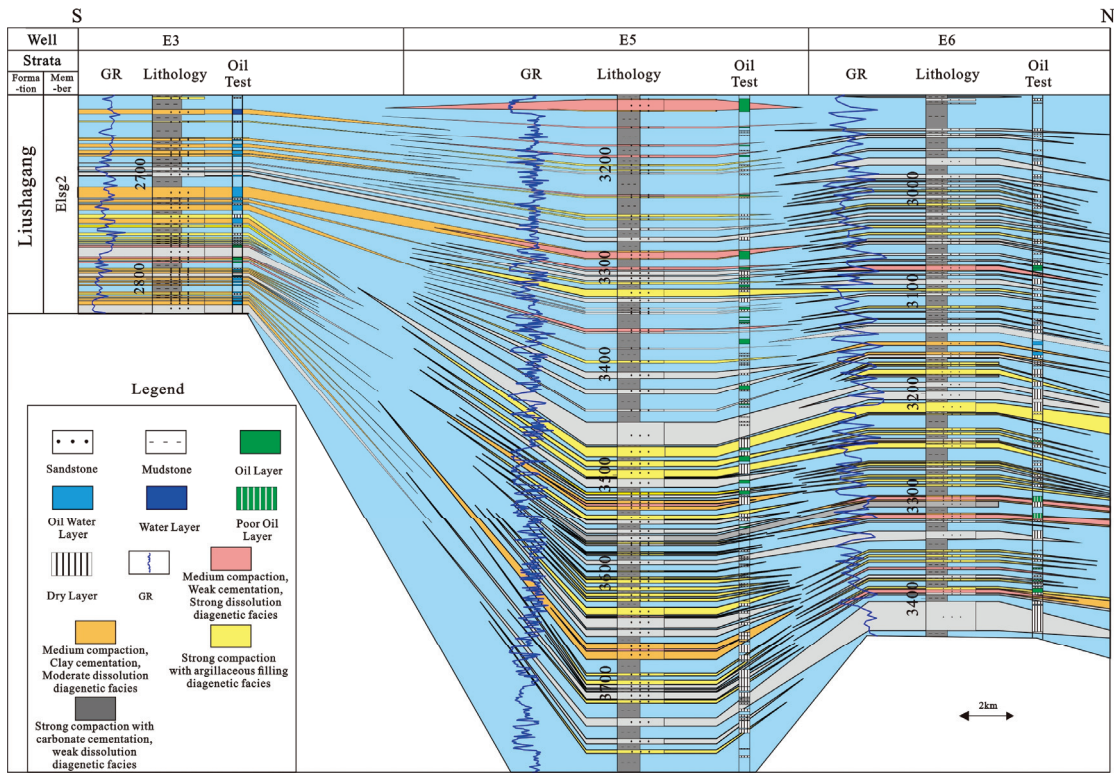


Figure 13. Cross-well diagenetic facies profile (wells E3–E6) for progradational fans in the Wushi Sag, Beibuwan Basin (section location is shown in Figure 1).

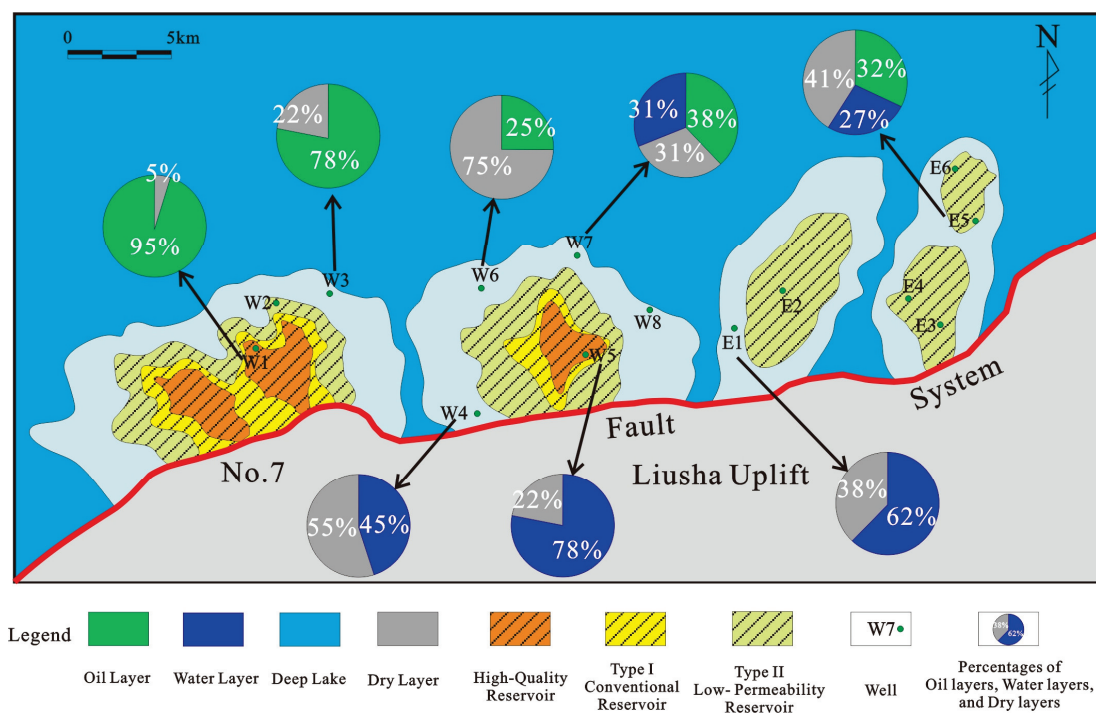
5.2. Distribution of High-Quality Reservoirs

In this study, reservoirs are classified by porosity and permeability into three types (Table 4): Type I (conventional): (porosity > 10%, permeability > 10 mD); Type II (low-permeability): (porosity 5–10%, permeability 1–10 mD); and Type III (tight): (porosity < 5%, permeability < 1 mD).

Table 4. Reservoir classification standards.

Reservoir Type	Porosity/(%)	Permeability/(mD)
Type I Conventional Reservoirs	>10%	>10 mD
Type II Low-Permeability Reservoirs	5–10%	1–10 mD
Type III Tight Reservoirs	<5%	<1 mD

Based on sedimentary and diagenetic facies characteristics, migratory fans in the southern steep-slope zone of the Wushi Sag are dominated by Type I–II reservoirs. Well W1 is located in a sweet spot reservoir, surrounded by Type I conventional and Type II low-permeability reservoirs, with Type III tight reservoirs at the margins. Similarly, well W5 lies in a sweet spot reservoir, with Type I–II reservoirs nearby and abundant Type III reservoirs on the outer edge. Sweet spot and Type I reservoirs form an annular distribution and occupy a relatively large area. Overall, the reservoirs show high oil-bearing properties and are dominated by oil layers (Figure 14).

**Figure 14.** Distribution of high-quality reservoirs and oil-bearing characteristics of migratory and progradational fans in the southern steep-slope zone of the Wushi Sag, Beibuwan Basin.

Progradational fans are dominated by Type II–III reservoirs. Well E2 is located in a Type II reservoir with Type III tight reservoirs at the margins. Wells E3, E4, E5, and E6 are also within Type II reservoirs, again bordered by Type III reservoirs. Type II reservoirs are limited in extent, occurring mainly in the middle of sand bodies in isolated islands and channel-like patterns. Overall, these reservoirs have low oil-bearing properties and are dominated by dry layers (Figure 14).

Migratory fan reservoirs are primarily controlled by shale content, are dominated by Type I–II diagenetic facies, and exhibit good physical properties, making them high-quality reservoirs. Progradational fan reservoirs are influenced by both shale content and carbonate

cementation, dominated by Type III–IV facies, with poor physical properties, making them lower-quality reservoirs.

5.3. Reservoir Model

Considering the controlling factors and differences between migratory and progradational fans in the southern steep-slope zone, prediction models for high-quality reservoirs were developed, including separate models for migratory progradational systems.

The migratory reservoir model is primarily fed by composite drainage systems with long transport distances, wide catchments, and abundant material supply. It is characterized by wide, deep V-shaped valleys that facilitate sediment input. Boundaries are marked by large steep-slope faults, and the system occurs in fault transfer zones with strong activity, displaying a “gentle-then-steep” profile. The lithology consists mainly of pebble-bearing medium-to-fine-grained sandstones interbedded with mudstones, with high sand content. It represents fan–delta–front subfacies with considerable thickness and lateral extend. Grains show point-to-line contacts, with compaction, abundant clay cement, and moderate cementation, resulting in relatively high porosity and permeability. Diagenesis is dominated by Type I facies (medium compaction, medium dissolution, weak cementation) and Type II facies (medium–strong compaction, clay mineral cementation, moderate dissolution), producing primarily Type I–II reservoirs (Figure 15A).

The progradational reservoir model is mainly supplied by a single drainage system, with a short transport distance, limited catchments, and low sediment supply. It features narrow, shallow U-shaped valleys where sediment progrades forward with minimal lateral migration. Boundaries are defined by steep-slope faults, and the system lies in fault transfer zones with weak activity, showing a “steep-then-gentle” profile. The lithology consists of interbedded medium-to-fine-grained sandstones and mudstones, with low sand content. It represents fan–delta–front subfacies with thinner, more restricted deposits. Grains exhibit line-to-concavo-convex contacts and strong compaction. Both clay and carbonate cements are well developed, resulting in strong cementation, low porosity, and low permeability. Diagenesis is dominated by Type III facies (medium–strong compaction, clay filling) and Type IV facies (medium compaction, strong carbonate cementation, weak dissolution), producing primarily Type II–III reservoirs (Figure 15B).

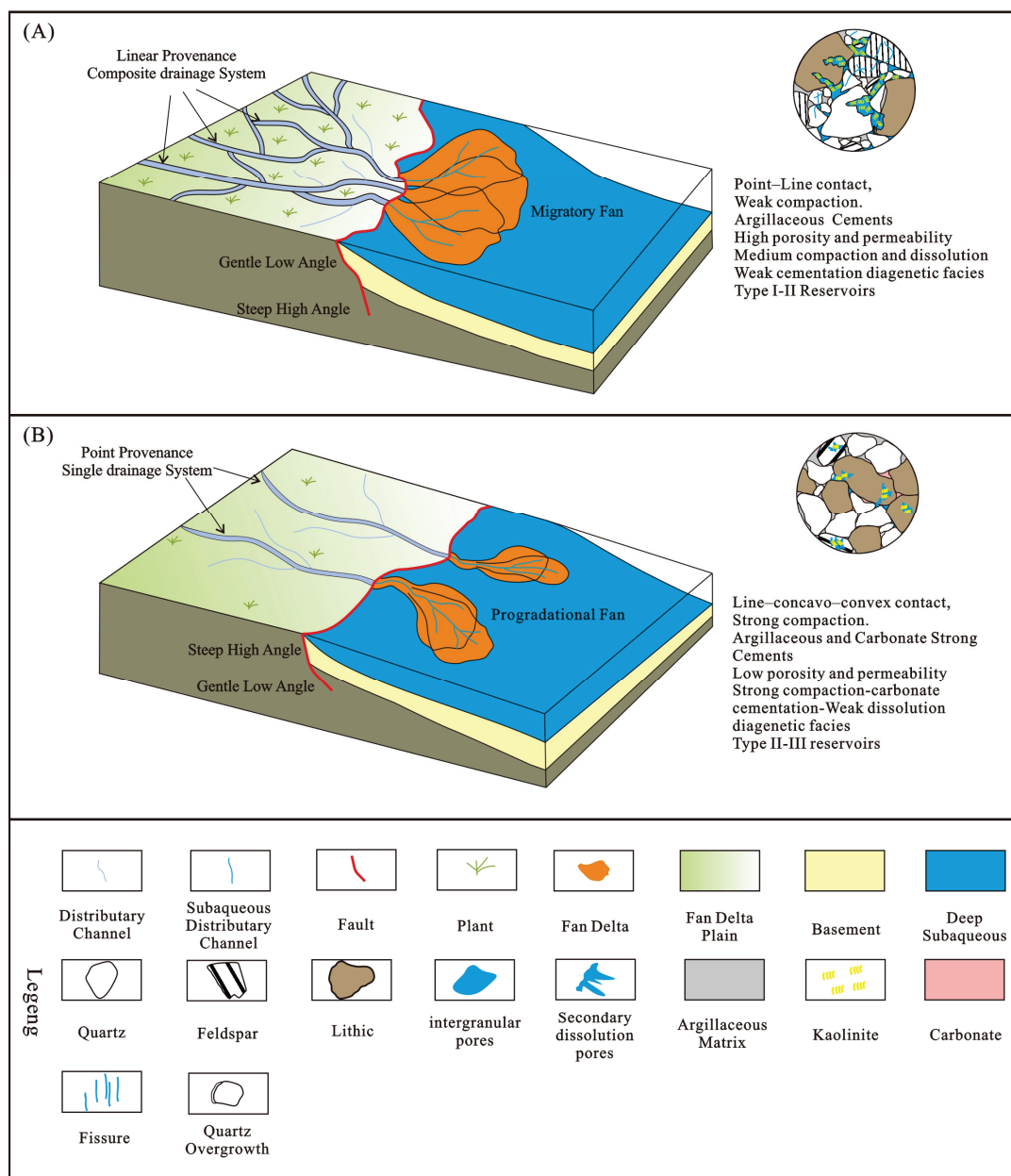


Figure 15. Reservoir prediction model of the (A) migratory fans and (B) progradational fans in the WuShi Sag, Beibuwan Basin.

6. Conclusions

The study area is located in the southern steep-slope zone of the Wushi Sag, Beibuwan Basin, South China Sea. Using 3D seismic data, core samples, drilling and logging data, thin sections, and laboratory analysis, this study compares the sedimentary and reservoir characteristics of migratory and progradational fan deltas and summarizes reservoir models for both types. The findings provide theoretical support for future oil and gas exploration and development in the Wushi Sag.

1. In the Second Member of the Liushagang Formation, in the southern steep-slope zone of the Wushi Sag (Beibuwan Basin), both migratory and progradational fan delta systems are developed. By comparing these systems, their sedimentary and reservoir characteristics were summarized, and predictive reservoir development models for both fan types were established.

2. The integration of sedimentary and reservoir characteristics clarifies the key differences between the two fan types. The development of sedimentary factors such as sources, channels, boundaries, and sinks controls fan development at the macroscopic scale, while reservoir factors such as the diagenetic facies types and high-quality reservoir distribution control it microscopically. Migratory fans exhibit superior sedimentary and reservoir conditions compared to progradational fans, making them the primary targets for future exploration.
3. Two reservoir development models are proposed, as follows:

The Migratory Fan Model is characterized by moderate burial depth, extensive drainage systems, wide and deep transport channels, and ample sediment supply and develops in fault transfer zones with strong fault activity; its lithology is dominated by gravelly coarse-to medium-grained sandstones, mainly in fan–delta–front distributary channel microfacies. Diagenesis is weak, resulting in high porosity and permeability and predominantly Type I–II reservoirs.

The Progradational Fan Model is characterized by greater burial depth, short drainage systems, narrow and shallow transport channels, and limited sediment supply. Developed in fault transfer zones with weak fault activity, its lithology consists of medium sandstones interbedded with mudstones, mainly in fan–delta–front interdistributary bay microfacies. Strong diagenesis leads to lower porosity and permeability and predominantly Type II–III reservoirs.

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Article

Effects of Submarine Methane-Rich Fluids on Gas Hydrate Production During Depressurization

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Abstract: Submarine methane-rich fluids migrating through geological conduits significantly influence gas hydrate production during depressurization. However, the coupled effects of methane, water, and heat delivered by these fluids on hydrate dissociation and methane recovery remain unclear. This study establishes a conceptual coupled numerical model of “pressure reduction–fluid response–reservoir evolution” based on reservoir parameters from Well W11 in the Shenhu area, South China Sea (SCS), and representative conduit characteristics. Hydrate dissociation and gas production are simulated under steady pressure reduction conditions with varying fluid invasion scenarios. Results show that the invasion of methane-rich fluid into gas hydrate systems exhibits a three-phase impact on gas production dynamics. Initially, the invasion has little effect on gas production; in the intermediate stage, it temporarily inhibits gas production; and under sustained invasion, it significantly enhances gas production. Limited water inflow with enhanced heat input promotes efficient hydrate-derived gas recovery. High methane flux enhances gas production while limiting hydrate dissociation. Excessive methane input may induce secondary hydrate formation, with the amount of newly formed hydrate exceeding that of the dissociated hydrate in the reservoir. A strong synergistic “1 + 1 > 2” effect occurs under low water or methane invasion, increasing gas output up to 4.3 times compared with a no-invasion case. These findings enhance understanding of dynamic hydrate exploitation systems and support the safe and efficient co-production of gas hydrates and associated deep gas.

Keywords: gas hydrate; methane-rich fluids; depressurization-induced production; fluid–hydrate interaction; numerical simulation; South China Sea

1. Introduction

Natural gas hydrates are widely distributed in marine and permafrost regions, including the Gulf of Mexico in the USA, the Nankai Trough in Japan, the South China Sea in China, and the Arctic margins, and are characterized by abundant reserves and environmentally friendly characteristics [1,2]. As the largest global reservoir of organic carbon, they are recognized as a promising unconventional energy resource with great potential to contribute to future low-carbon energy supply and climate change mitigation [3,4].

Marine gas hydrates are mainly composed of methane, and their occurrence and stability are dynamically controlled by temperature, pressure, sedimentary environment, and deep fluid migration [5,6]. While numerous studies have investigated hydrate stability under static thermodynamic conditions or assessed individual factors (e.g., pressure, temperature, and tectonic activity) controlling hydrate distribution and dissociation [7–12],

few have systematically examined how fluid conduits regulate marine gas hydrate systems under multiphysical coupling dynamics. In particular, the influence of fluid conduits in hydrate-bearing reservoirs on gas production and reservoir evolution during depressurization, a method currently regarded as the most effective method for marine gas hydrate exploitation, remains poorly understood.

In nature, fluid conduit-associated gas hydrate systems are widespread and typically exhibit high accumulation efficiency and hydrate saturation (Figure 1) [13–15]. In this dynamic system, fluid conduits act as expressways, transporting deep methane-rich fluids into the hydrate stability zone, regulating methane supply and entrapment efficiency [16]. When gas pressure beneath the hydrate-bearing reservoir exceeds its sealing threshold, gas rapidly migrates through these conduits toward the seafloor, potentially triggering methane seepage or secondary hydrate formation [17–21]. These observations indicate that the properties of fluids within these conduits control the dynamic evolution of hydrate systems. Although several studies have investigated fluid migration in such conduits, they mostly adopt a single-factor perspective, focusing on methane flux [17,22]. In hydrate production, previous studies have revealed that the combined effect of low pressure at the production well and high pressure within the conduits can induce methane accumulation near the wellhead, thereby reducing direct methane leakage [23]. Physical simulations have further shown that when high-temperature and high-pressure deep natural gas rapidly invades the hydrate reservoir through gas chimneys, only a small portion of the energy is utilized for hydrate dissociation [24]. In real geological settings, methane, water, and heat within fluids often act together to drive hydrate dissociation, reformation, and re-accumulation. Such interactions are critical for depressurization-induced production, where external fluxes strongly affect methane recovery. However, existing studies generally neglect the co-evolving interactions among methane, water, and heat, and how different methane, water, and heat fluxes within conduits control hydrate behavior during depressurization remains unclear.

In the northern South China Sea, widespread faults and gas chimneys act as critical fluid conduits for the upward migration of methane-rich fluids (Figure 1), exerting a significant influence on the evolution of hydrate reservoirs in response to pressure changes [25]. To investigate the response mechanisms of fluid conduit-controlled gas hydrate systems during depressurization, this study focuses on the hydrate-bearing reservoir of Well W11 in the Shenhu area, South China Sea. Based on in situ measured reservoir parameters (e.g., porosity, permeability, hydrate saturation) and key physical parameters representative of typical fluid conduits, a two-dimensional conceptual coupled numerical model of “pressure reduction–fluid response–reservoir evolution” was developed. Distinct from previous single-factor studies centered on methane flux, our model systematically introduces the co-evolution of methane, water, and heat within fluids, simulating their influence on hydrate dissociation and gas production under depressurization-induced production scenarios. Our study sequentially explores (i) the controlling effect of fluid conduit presence/absence on gas production and reservoir evolution; (ii) the regulatory mechanisms of methane, water, and heat supply intensity on reservoir evolution and gas production; and (iii) the key parameters controlling gas production from hydrate dissociation under depressurization. The insights obtained provide critical guidance for assessing hydrate production potential in highly dynamic zones and for optimizing depressurization strategies in conduit-associated gas hydrate systems.

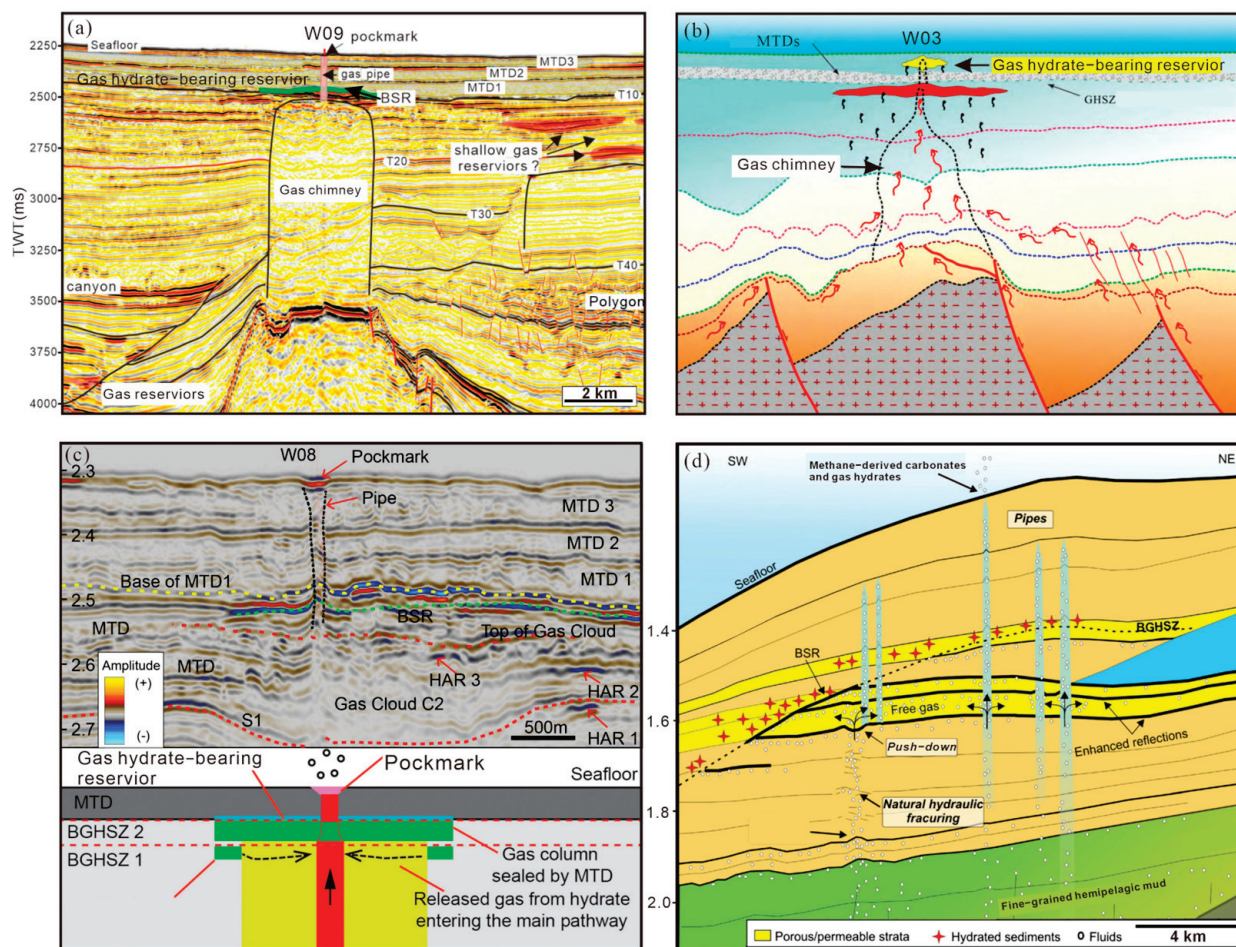


Figure 1. Gas hydrate reservoirs associated with methane-rich fluid conduits at (a) W09, (b) W03, and (c) W08 in the Qiongdongnan Basin (modified from [26–29]), and (d) on the Norwegian continental slope (adapted from [30]). Abbreviations: MTD—mass transport deposit; HAR—high amplitude reflection; GHSZ—gas hydrate stability zone; BGHSZ—base of gas hydrate stability zone; BSR—bottom-simulating reflection; SW—Southwest; NE—Northeast. W09, W03, and W08 indicate well locations.

2. Simulation Methodology

2.1. Reservoir Background and Initial Conditions

The gas hydrate-bearing reservoir modeled in this study was conceptualized using geological parameters from the Shenhu area of the SCS (Figure 2), a region characterized by well-developed fault systems [25,31]. The reservoir properties, including the physical and geological characteristics, were derived from published data of Well W11 in the Shenhu area (Figure 2b,c) [32,33], ensuring a representative and realistic model for simulation purposes. In the established numerical model, the initial temperature and pressure conditions of the reservoir were set at 14.28 °C and 15.76 MPa, respectively, which reflect the typical conditions of the gas hydrate stability zone in this area. The hydrate-bearing reservoir was defined with a permeability of 0.22 mD (equivalent to $2.20 \times 10^{-16} \text{ m}^2$), a porosity of 34.5%, and an initial hydrate saturation of 34.0%.

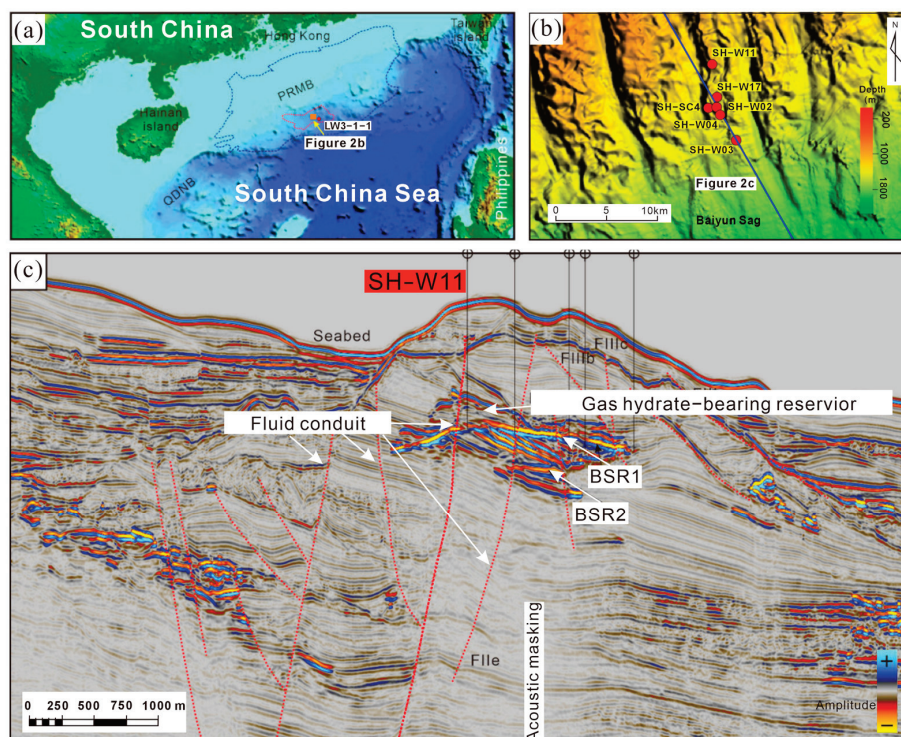


Figure 2. (a) Location of the study area in the Baiyun Sag, Pearl River Mouth Basin (PRMB), northern South China Sea; (b) Submarine geomorphology and borehole distribution in the Shenhu gas hydrate reservoir; (c) Schematic of the fluid conduit-associated gas hydrate system in Well W11 (modified from [25]). Abbreviations: QDNB—Qiongdongnan Basin; FII—Fault; BSR—bottom-simulating reflection. Wells such as SH-W11, SH-W17, and LW3-1-1 indicate the borehole locations.

2.2. Simulation Code

The pressure reduction-driven dissociation process was simulated using the TOUGH + Hydrate v1.5 (Lawrence Berkeley National Laboratory, Berkeley, CA, USA) [34]. This simulator implements dual modeling approaches for gas hydrate behavior, combining thermodynamic equilibrium principles with kinetic reaction analysis. This computational tool evaluates heat transfer phenomena and tracks four primary components (H_2O , CH_4 , hydrate, and water-soluble inhibitors such as salts or alcohols) distributed across gas phase, liquid phase, ice phase, and hydrate phase. It comprehensively simulates phase transition dynamics, associated thermal effects, and inhibitor impacts, while modeling various dissociation methods including depressurization, thermal stimulation, salting-out effects, and inhibitor-induced effects [35].

2.3. Model Construction, Fluid Invasion Flux and Depressurization Simulation

Considering that reservoirs such as those at the Norwegian continental slope and Well W11 commonly contain multiple fault or gas chimney clusters, this conceptual model assumes that the physical fields in the reservoir between these conduit clusters are treated as mirrored (or symmetric) for modeling simplification.

Based on this assumption, a 2D numerical model of fluid conduit-associated gas hydrate system was constructed with dimensions of 50 m (x) $\times$ 50 m (y) $\times$ 1 m (z) (Figure 3). The grid spacing along both the x - and y -axes ranged from 0.1 to 0.5 m, yielding a total of $247 \times 247 = 61,009$ grid cells. The 1 m thickness in the z -direction defines a computational layer only and does not participate in fluid or heat transport. All four lateral faces are treated as constant-temperature, impermeable boundaries, with no fluid or heat exchange across them. Pressure evolution is governed entirely by the internal reservoir dynamics.

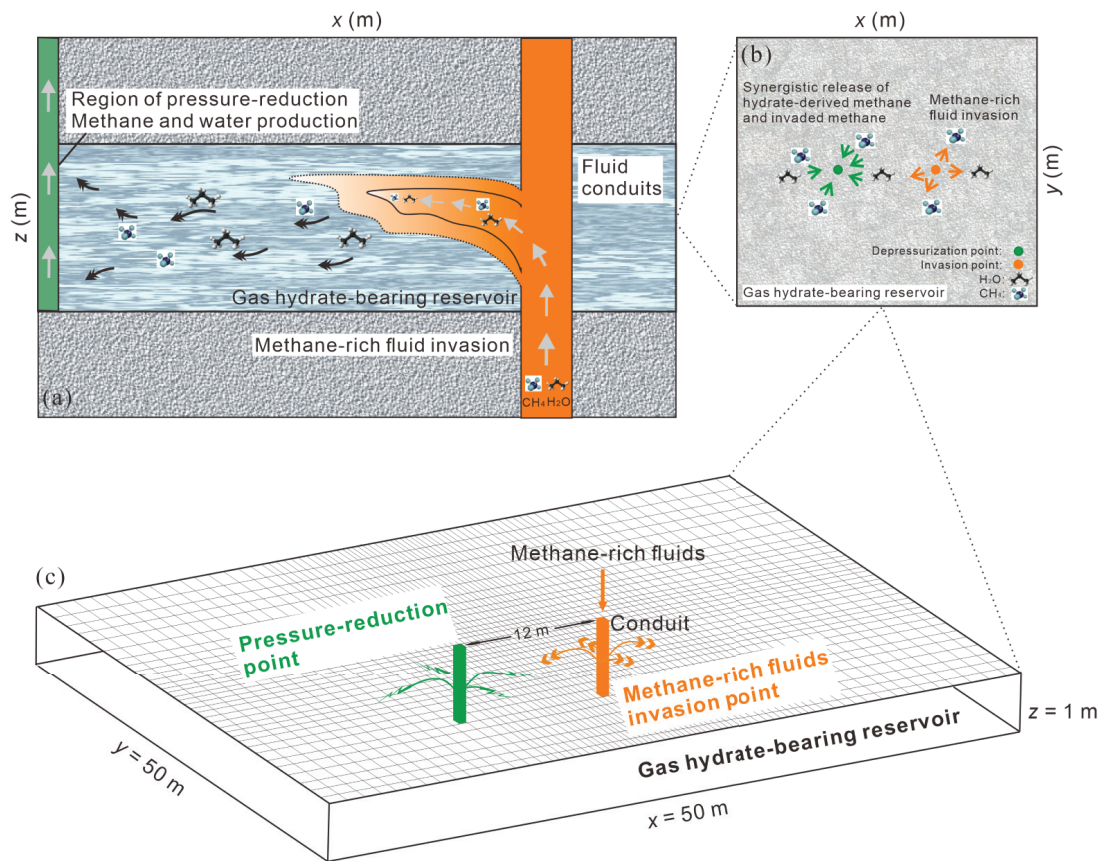


Figure 3. (a) Schematic of fluid invasion and depressurization-driven gas hydrate production in the x – z profile; (b) Schematic of fluid invasion and depressurization-driven gas hydrate reservoir evolution in the x – y plane; (c) Conceptual 2D coupled model of “pressure reduction–fluid response–reservoir evolution” with a 1 m computational layer in the z -direction (no fluid or heat transfer) and four lateral faces set as constant-temperature and impermeable boundaries. The green point denotes the pressure reduction point, the orange point indicates the methane-rich fluid invasion point, and the distance between them is 12 m. All arrows in the figure indicate the direction of fluid movement.

The pressure reduction point and methane-rich fluid invasion point were located 12 m apart (Figure 3c), with the pressure reduction point maintained at a target pressure of 4.5 MPa. The current approximation for high-permeability fluid conduits is a simplistic conceptualization, but it enables direct fluid leakage. Methane was introduced as a dissolved phase through the methane-rich fluid invasion point. The model’s key parameters, including reservoir parameters, fluid conduit characteristics, and pressure reduction point parameters, are detailed in Table 1.

In this study, Case 1 represents the pressure reduction-only dissociation scenario, while Case 2 serves as the baseline case involving both pressure reduction and methane-rich fluids invasion. In Case 2, high-temperature methane-rich fluid was invaded at rates of 1.54×10^{-4} kg/s for CH₄ (equivalent to 19.60 ST m³/day) and 1.00×10^{-3} kg/s for H₂O, accompanied by a heat supply input of 1.20×10^3 W.

A sensitivity analysis was performed to assess the influence of varying invasion characteristics, including water invasion rate, methane invasion rate, and heat supply rate. The specific sensitivity cases are presented in Table 2. In Cases W1–W12, the water invasion rate ranged from 2.00×10^{-5} to 1.60×10^{-3} kg/s; in Cases M1–M18, the methane invasion rate varied between 1.00×10^{-6} and 1.60×10^{-3} kg/s; and in Cases H1–H13, the heat supply rate was adjusted from 1.60×10^3 to 1.00×10^1 W.

Table 1. Physical model parameters [32,33].

Parameter	Value	Parameter	Value
Reservoir basic parameters			
Permeability/m ²	2.20×10^{-16}	Seawater salinity/wt%	3.05
Porosity/%	34.5	Seawater density/(kg·m ³)	1035
Hydrate saturation/%	34.0	Thermal conductivity (wet)/(W·m ⁻¹ ·°C)	2.917
Particle density/(kg·m ⁻³)	2700	Thermal conductivity (dry)/(W·m ⁻¹ ·°C)	1.000
Specific heat capacity/(J·kg ⁻¹ ·C ⁻¹)	1000		
Relative permeability model [34]			
$K_{rA} = (S_A^*)^n$		$K_{rG} = (S_G^*)^n$	
$S_A^* = (S_A - S_{irA})/(1 - S_{irA})$		$S_G^* = (S_G - S_{irG})/(1 - S_{irA})$	
S_{irA}	0.3	n_G	3
S_{irG}	0.03	n	5
Capillary pressure model [36]			
$P_{cap} = -P_0 [(S^*)^{-1/\lambda} - 1]^{1-\lambda}$		$S^* = (S_A - S_{irA})/(S_{mxA} - S_{irA})$	
P_0/P_a	10^5	S_{mxA}	1.00
λ	0.45	S_{irA}	0.50
Pressure reduction point parameters			
Permeability/m ²	5.0×10^{-9}	Capillary pressure	0
Porosity/%	100	Area/m ²	0.01
Invasion point parameters			
Porosity/%	100	Relative permeability in conduit	$k_{rA} = S_A,$ $k_{rG} = S_G$
Capillary pressure	0	Area/m ²	0.01
Gas composition	100% CH ₄		

Table 2. Simulation case design involving pressure reduction and methane-rich fluid invasion.

Case ID	Water Invasion Rate (kg/s)	Case ID	Methane Invasion Rate (kg/s)	Case ID	Heat Supply Rate (W)
W1	2.00×10^{-5}	M1	1.00×10^{-6}	H1	1.00×10^3
W2	4.00×10^{-5}	M2	1.20×10^{-6}	2	1.20×10^3
W3	6.00×10^{-5}	M3	1.40×10^{-6}	H2	1.40×10^3
W4	8.00×10^{-5}	M4	1.60×10^{-6}	H3	1.60×10^3
W5	1.00×10^{-4}	M5	1.80×10^{-6}	H4	1.80×10^3
W6	2.00×10^{-4}	M6	1.00×10^{-5}	H5	1.00×10^2
W7	4.00×10^{-4}	M7	1.20×10^{-5}	H6	1.20×10^2
W8	6.00×10^{-4}	M8	1.40×10^{-5}	H7	1.40×10^2
W9	8.00×10^{-4}	M9	1.60×10^{-5}	H8	1.60×10^2
2	1.00×10^{-3}	M10	1.80×10^{-5}	H9	1.80×10^2
W10	1.20×10^{-3}	M11	1.00×10^{-4}	H10	1.00×10^1
W11	1.40×10^{-3}	M12	1.20×10^{-4}	H11	1.20×10^1
W12	1.60×10^{-3}	M13	1.40×10^{-4}	H12	1.40×10^1
		2	1.54×10^{-4}	H13	1.60×10^1
		M14	1.80×10^{-4}		
		M15	1.00×10^{-3}		
		M16	1.20×10^{-3}		
		M17	1.40×10^{-3}		
		M18	1.60×10^{-3}		

Notes: “W”, “M”, and “H” represent water invasion, methane invasion, and heat-supply cases, respectively.

The selected fluid fluxes exceed natural measurements [17,23], primarily to simulate the transient increase in conduit flow that occurs during pressure reduction in actual geological systems.

3. Results and Discussion

3.1. Effect of Methane-Rich Fluid Invasion

By comparing Cases 1 and 2, this section analyzes how methane-rich fluid invasion affects reservoir physical property evolution and gas production behavior during depressurization, and investigates the mechanisms behind the observed gas production patterns.

3.1.1. Reservoir Physical Fields Evolution

The time-dependent reservoir evolution of physical fields in Case 1 is presented in Figure S1 in the Supplementary Material. As shown in Figure S1a,b, a circular low-pressure and low-temperature zone forms around the pressure reduction point in the hydrate reservoir under depressurization conditions. The circular low-pressure zone progressively expands with continued pressure reduction (Figure S1a). Initially, the circular low-temperature zone exhibits a “moderate-low-moderate-high” radial thermal gradient extending from the pressure reduction point (Figure S1b). After $t = 60$ days, the temperature distribution evolves into a “low-moderate-high” gradient, likely due to the endothermic effect associated with hydrate dissociation. In addition to significant changes in reservoir temperature and pressure, the hydrate saturation around the pressure reduction point declines markedly due to hydrate dissociation (Figure S1c). Gas and water released from hydrate dissociation increase gas and water saturations around the pressure reduction point (Figure S1d,e).

The time-dependent evolution of reservoir physical fields in Case 2 is shown in Figure 4. The reservoir pressure around the pressure reduction point decreases under depressurization conditions (Figure 4a). The low-pressure zone progressively expands as depressurization continues until $t = 60$ days. Meanwhile, pressure near the methane-rich fluid invasion point increases due to continuous fluid invasion. After $t = 120$ days, the low-pressure zone near the pressure reduction point contracts significantly due to methane-rich fluid invasion. By $t = 360$ days, pressure around the methane-rich fluid invasion point also declines.

During the early pressure reduction, the temperature around the pressure reduction point dropped significantly (Figure 4b). As depressurization progressed, the low-temperature zone surrounding this point expanded gradually. The temperature around the methane-rich fluid invasion point remained relatively high, and the high-temperature zone continued to grow. By $t = 60$ days, the circular low-temperature region around the pressure reduction point was strongly influenced by the invading high-temperature methane-rich fluid. After $t = 120$ days, the high-temperature zone surrounding the fluid invasion point became irregular in shape. This change was caused by the combined effects of depressurization.

With the continuous depressurization, the hydrate dissociation zone around the pressure reduction point expanded (Figure 4c). Significant hydrate dissociation also occurred around the methane-rich fluid invasion point, whose dissociation zone grew progressively. Comparatively, the extent of hydrate dissociation at the methane-rich fluid invasion point exceeded that around the pressure reduction point. By $t = 360$ days, the hydrate dissociation zones driven by pressure reduction and methane-rich fluid invasion merged into a connected region. Notably, a ring-shaped zone of high hydrate saturation appears at the outer boundary of the dissociation area near the methane-rich fluid invasion point,

indicating secondary hydrate formation. This secondary hydrate formation is promoted by the relatively low temperature and elevated pressure caused by fluid invasion.

As hydrate dissociation progressed, methane accumulated around both the pressure reduction and methane-rich fluid invasion points, forming radial concentration gradients (Figure 4d), and gradually expanded with prolonged fluid invasion. After $t = 120$ days, methane from the invasion point migrated to the pressure reduction point.

The water saturation surrounding the pressure reduction point remained relatively high due to hydrate dissociation (Figure 4e). Near the methane-rich fluid invasion point, water saturation also increased markedly due to hydrate dissociation and fluid invasion, forming a distinct concentric “high–low–high” saturation pattern radiating outward. After $t = 120$ days, the low-water-saturation zone near the invasion point expanded into the pressure reduction-controlled region. The formation of secondary hydrate consumed water and methane, resulting in an annular zone of low water and gas saturation (Figure 4d,e).

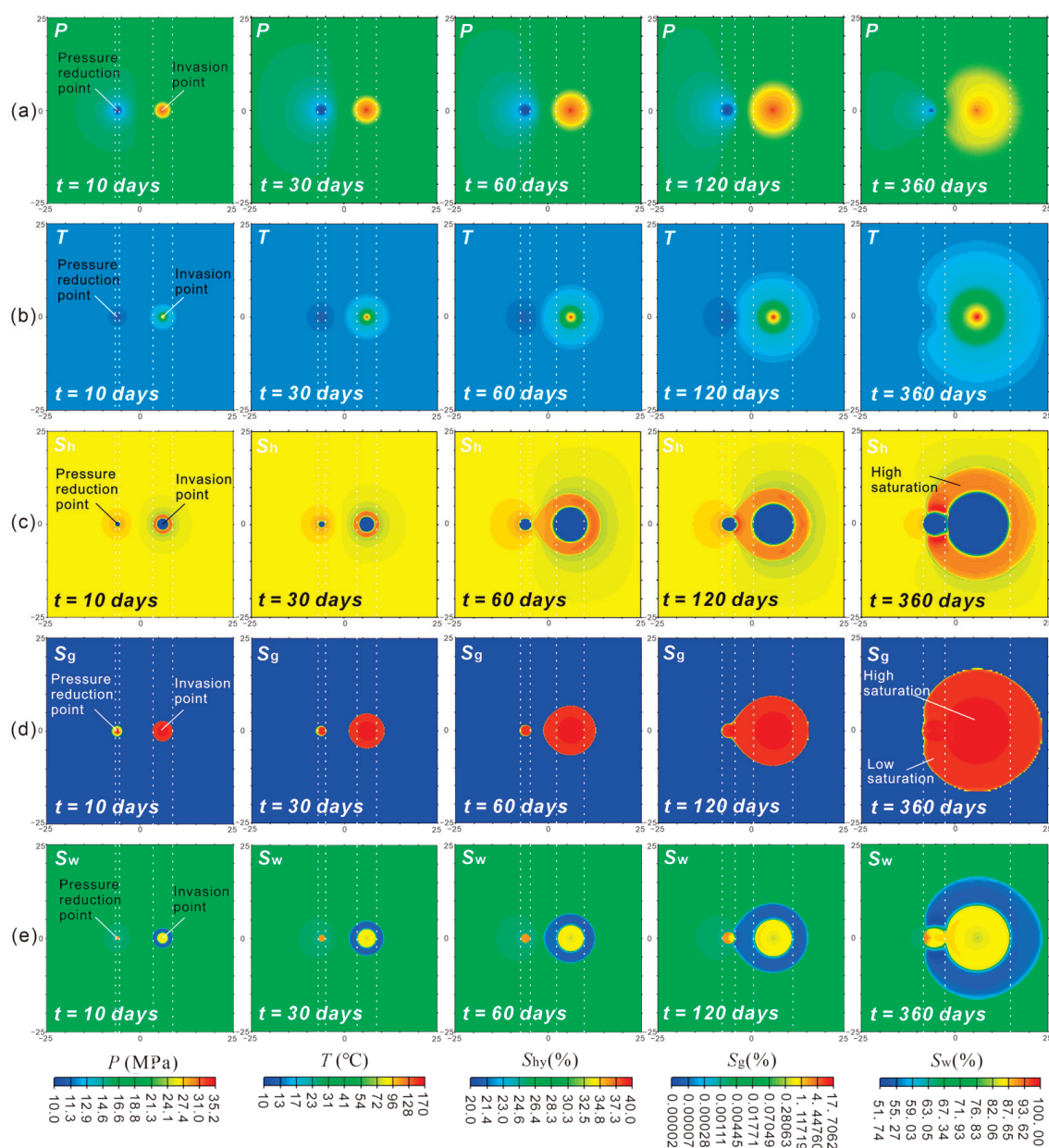


Figure 4. Evolution of reservoir properties in Case 2 (50 m × 50 m): (a) pressure (P), (b) temperature (T), (c) hydrate saturation (S_h), (d) gas saturation (S_g), and (e) water saturation (S_w).

3.1.2. Gas Production Behavior

As shown in Figure 5, the gas production rate in Case 1 follows a pattern of “rapid short-term decline followed by gradual long-term reduction”. Correspondingly, the cumulative gas production in Case 1 increases steadily (Figure 5b). In contrast, Case 2 exhibits more complex gas production behavior (Figure 5a), characterized by an initial sharp decline, a gradual reduction during the intermediate stage, and a progressive increase under prolonged depressurization. Correspondingly, the cumulative gas production in Case 2 rises significantly (Figure 5b).

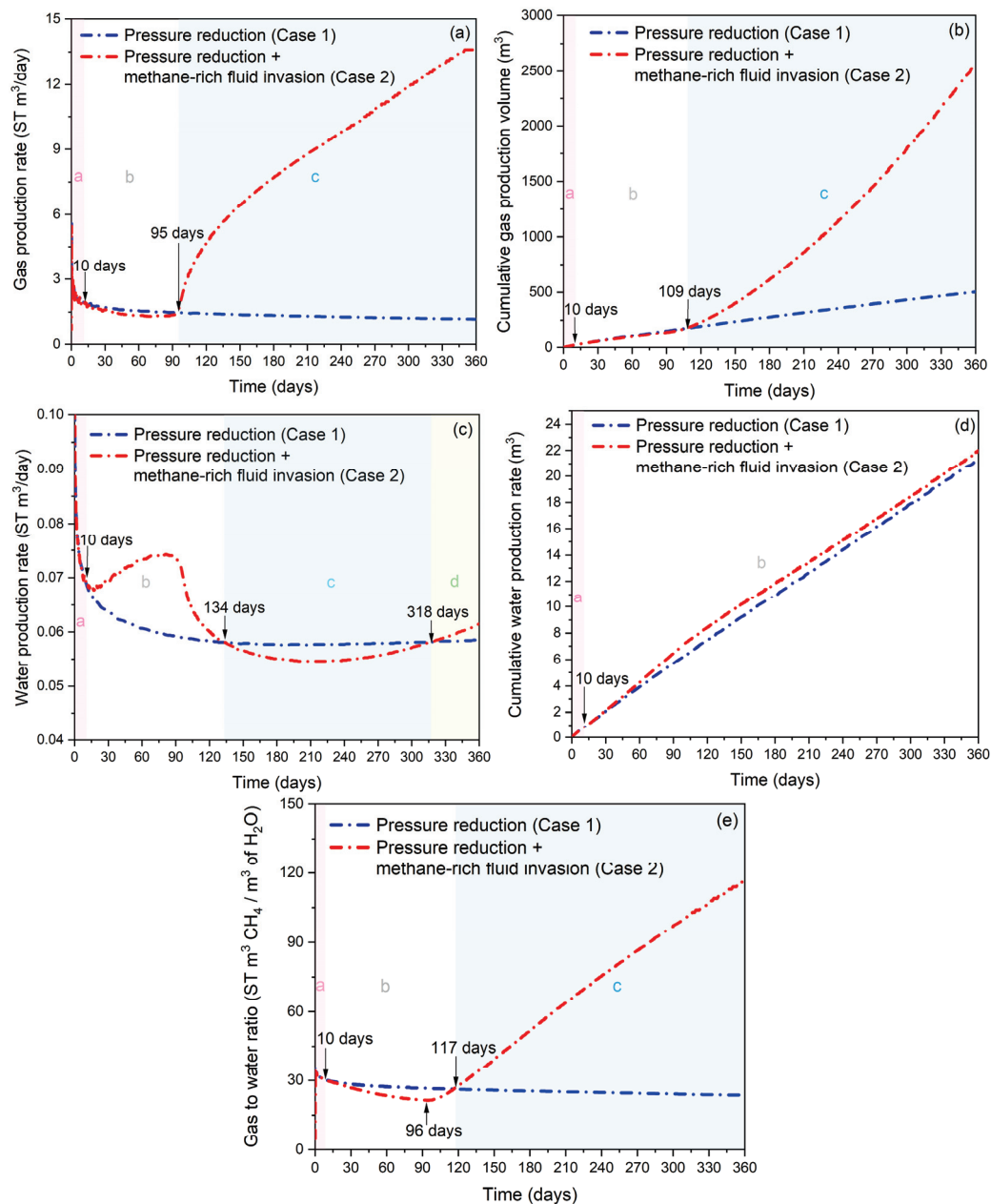


Figure 5. Evolution of (a) gas production rate, (b) gas production volume, (c) water production rate, (d) water production volume, and (e) gas–water ratio during the depressurization-induced dissociation process in Cases 1 and 2. The letters a, b, c, and d in the figure represent different blocks (shown in red, white, blue, and yellow, respectively). The main purpose of dividing these blocks is to illustrate the changes in gas and water production relationships between Case 1 and Case 2. “+” indicates the simultaneous presence of both depressurization and methane-rich fluid invasion processes.

The water production rate in Case 1 follows a pattern of “rapid decline–gradual reduction–slow increase” pattern under reduced-pressure conditions (Figure 5c), resulting in a steady rise in cumulative water production (Figure 5d). In contrast, Case 2 displays a W-shaped variation in rate (“rapid decline–significant increase–sharp decrease–gradual rise” in Figure 5c), driving a continuous increase in cumulative water production (Figure 5d).

The gas–water ratio in Case 1 declines gradually throughout the pressure reduction period (Figure 5e). In contrast, Case 2 exhibits an initial decrease followed by a sharp increase after $t = 96$ days.

The gas and water production rates of Cases 1 and 2 were essentially similar before $t = 10$ days (Figure 5a,c). This behavior is primarily because, from $t = 10$ days onward, the invading methane-rich fluid began to influence the reservoir’s physical fields around the pressure reduction point, affecting gas and water production from hydrate dissociation (Figure S2).

After $t = 10$ days, Case 2 exhibits distinct production characteristics compared with Case 1 during prolonged pressure reduction: (1) the gas production rate remains lower than that of Case 1 between $t = 10$ –95 days but surpasses it after $t = 95$ days (Figure 5a); (2) the water production rate exceeds that of Case 1 between $t = 10$ –134 days and after $t = 318$ days (Figure 5c). This behavior is primarily attributed to the invasion of high-temperature methane-rich fluids in Case 2. As exemplified by the reservoir conditions at $t = 30$ days, the reservoir properties surrounding the pressure reduction point in Case 2—including pressure, temperature, gas saturation, and water saturation—exhibit significant changes due to the invasion of methane-rich fluids (Figure S3b). In Case 2, the high gas saturation zone around the pressure reduction point in the hydrate reservoir is significantly decreased under the condition of methane-rich fluid invasion.

After $t = 95$ days, the high gas saturation zone surrounding the methane-rich fluid invasion point in Case 2 connected with the high gas saturation zone near the pressure reduction point (Figure 6a). The methane from the methane-rich fluid invasion point is extensively extracted due to depressurization effects, resulting in significant enhancement of gas production. The enhanced gas production in Case 2 induces reduction in water output. Moreover, capillary forces within the hydrate-bearing formation are enhanced under continuously increased hot methane invasion. Both dissociated hydrate water and invaded water are dominantly retained as irreducible saturation in pore spaces, thereby reducing water production while improving gas recovery efficiency [37]. Consequently, Case 2 exhibits a pronounced decline in water production rate after $t = 95$ days, ultimately dropping below Case 1 after $t = 134$ days.

After $t = 318$ days, the water production rate of Case 2 again exceeds that of Case 1. This increase is mainly due to the spatially heterogeneous water saturation distribution, which shows a distinct “high–low–high” transitional pattern extending from the methane-rich fluid invasion point toward the reservoir interior. With continuous invasion of methane-rich fluids, the extent of high-water-saturation zones surrounding the invasion point exhibits expansion. Before $t = 318$ days, only the low-water-saturation zones connect with the high-water-saturation zones near the pressure reduction point (Figure 6b). After $t = 318$ days, connectivity is established between the high-water-saturation zones and those surrounding the pressure reduction point, further enhancing water production in Case 2 and ultimately exceeding that of Case 1.

Although the water production rate in Case 2 is lower than Case 1 during the $t = 134$ –318 days period (Figure 5c), the cumulative water production in Case 2 consistently higher than Case 1 after $t = 10$ days (Figure 5d). After $t = 109$ days, the disparity in gas production between Case 2 and Case 1 becomes more obvious compared to their

water production differential (Figure 5b). Consequently, the gas–water ratio in Case 2 stays higher than in Case 1 after $t = 117$ days (Figure 5e).

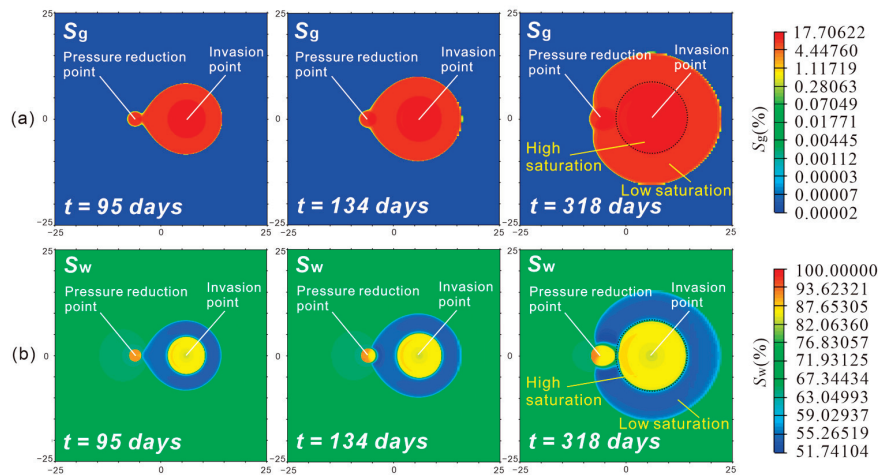


Figure 6. Spatial distributions of (a) gas saturation (S_g) and (b) water saturation (S_w) in Case 2 at $t = 95$, 134, and 318 days (50 m $\times$ 50 m).

3.1.3. Free Methane Volume in the Reservoir and Residual Hydrate Mass

Both Cases 1 and 2 show increased methane release from the hydrate-bearing reservoir during depressurization (Figure 7a). In comparison, Case 2 exhibits a more pronounced enhancement in cumulative methane release, increasing by more than ten times. The remaining mass of hydrate in the reservoir gradually decreases in both cases (Figure 7b). In Case 1, only a minor reduction occurs in hydrate mass (from 2.69×10^5 to 2.66×10^5 kg), whereas Case 2 shows a clear linear decline from 2.69×10^5 to 2.46×10^5 kg. The dissociation rate in Case 2 is 7.67 times higher than that in Case 1. During depressurization, the volume of free methane in the reservoir increases in both cases, with Case 2 displaying a more substantial cumulative enhancement (Figure 7b).

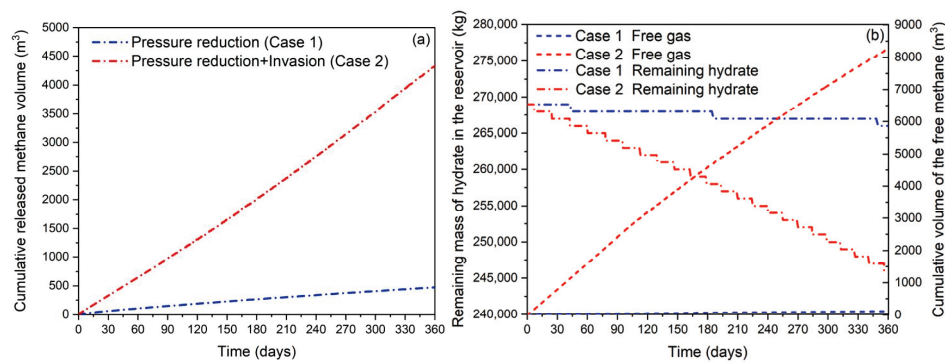


Figure 7. Evolution of (a) cumulative released methane volume (m^3) and (b) cumulative volume of free methane in the reservoir (m^3) and the remaining mass of hydrate in the reservoir (kg) for Case 1 and Case 2.

3.2. Effect of Methane-Rich Fluid Flux

To clarify the individual effects of water, methane, and heat on hydrate dissociation and gas production, 40 simulation cases were designed (Table S1 in the Supplementary Material), covering water-only, methane-only, and heat-only invasion scenarios. Comparative analysis of single-factor simulations (Figures S4–S6) and the multi-factor simulations in this section indicates that the influence mechanisms of water, methane, and heat are largely independent, forming the basis for the following discussion of their respective effects.

3.2.1. Effect of Water Invasion Rate

Compared to Case 1 (without methane-rich fluid invasion), the methane and water production rates, as well as the gas-to-water ratio in Cases W1–W12 and Case 2, exhibit distinct evolutionary trends (Figure 8). Although the water invasion rate influences methane and water production, the overall trend remains similar across cases. In the early stage ($t < 83$ days), increasing the water invasion rate exerts little influence on gas production, indicating a delayed response of hydrate dissociation to water influx. After $t = 83$ –103 days, when the gas production rates in Cases W1–W12 and Case 2 surpass that of Case 1, the gas production rate gradually declines with increasing water invasion rate (Figure 8a), with higher invasion rates causing a later crossover. The specific time at which the gas production rate significantly increases and exceeds that of Case 1 under different water invasion rates is shown in Table S2 in the Supplementary Material. Conversely, the water production rate shows a positive correlation with the water invasion rate (Figure 8b). At excessive water invasion rates (Cases W11 and W12), water production becomes dominant from approximately $t = 15$ days onward and remains consistently higher than in Case 1 throughout the simulation. For the gas-to-water ratio, sensitivity to water invasion rate is low before $t = 90$ days, but after this period, lower water invasion rates lead to earlier and more pronounced increases (Figure 8c).

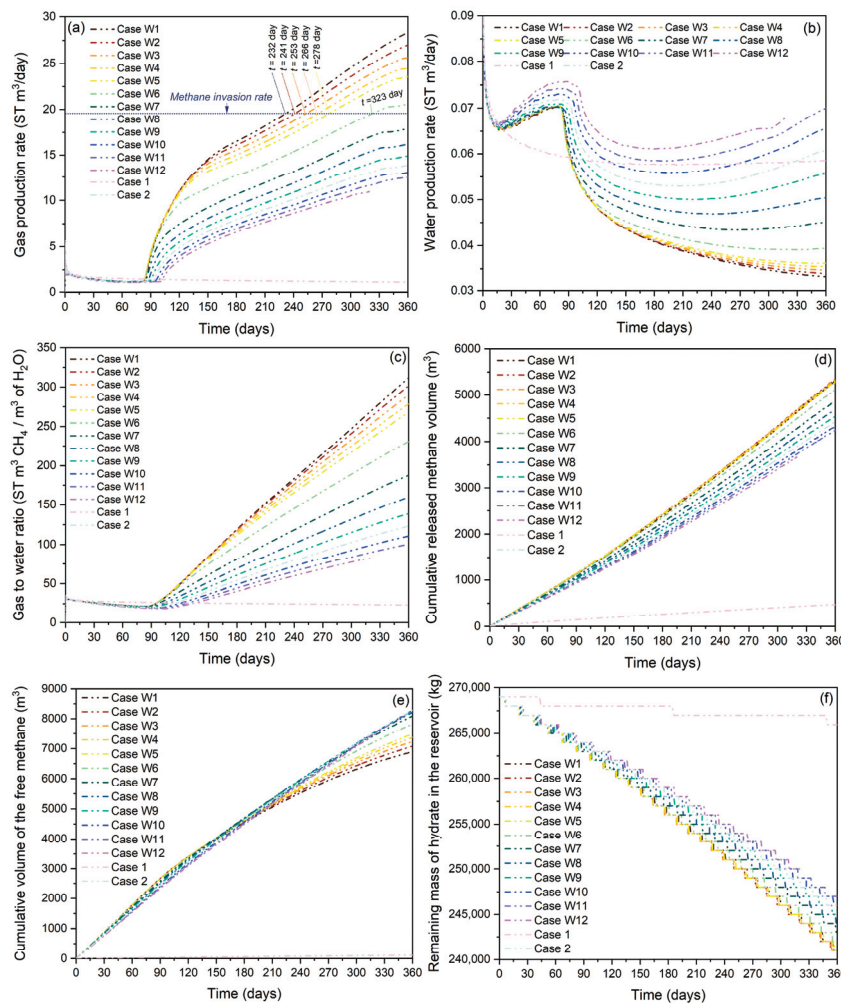


Figure 8. Evolution of (a) gas production rate (m³/day) at the pressure reduction point, (b) water production rate (m³/day) at the pressure reduction point, (c) gas-to-water ratio at the pressure reduction point, (d) cumulative released methane volume (m³), (e) cumulative volume of the free methane (m³) and (f) remaining mass of hydrate in the reservoir (kg) for Cases 1, 2, and W1–W12.

As shown in Figure 8d,e, regardless of the water invasion rate, both the gas production from hydrate dissociation and the free methane in the reservoir in Cases W10~W12 and Case 2 consistently exceed those in Case 1. However, the gas production from the hydrate reservoir decreases with increasing water invasion rate. The free methane in the reservoir exhibits a similar decreasing trend with increasing water invasion rate only before $t = 180$ days; after $t = 180$ days, it increases with higher water invasion rates. For Cases W10~W12 and Case 2, the remaining hydrate mass is lower than in Case 1 but increases with higher water invasion rates (Figure 8f).

As mentioned above, a high-water invasion rate decreases hydrate dissociation and gas production. The decrease in hydrate dissociation under high water invasion rates is mainly due to the following factors: high water invasion induces a stronger pressure increase in the reservoir (Figure 9a,f), inhibiting dissociation near the invasion point [38]. It also lowers the temperature near the invasion front (Figure 9b,g). Since hydrate dissociation is endothermic, the lower temperature further slows the process. Consequently, the hydrate dissociation zone near the fluid invasion area is smaller under high water invasion compared to low invasion rates (Figure 9c,h). Although the dissociation zone near the pressure reduction front is larger under high water invasion, the contrast in dissociation zone size is more pronounced near the fluid invasion front. As a result, less hydrate dissociates under high water invasion rates.

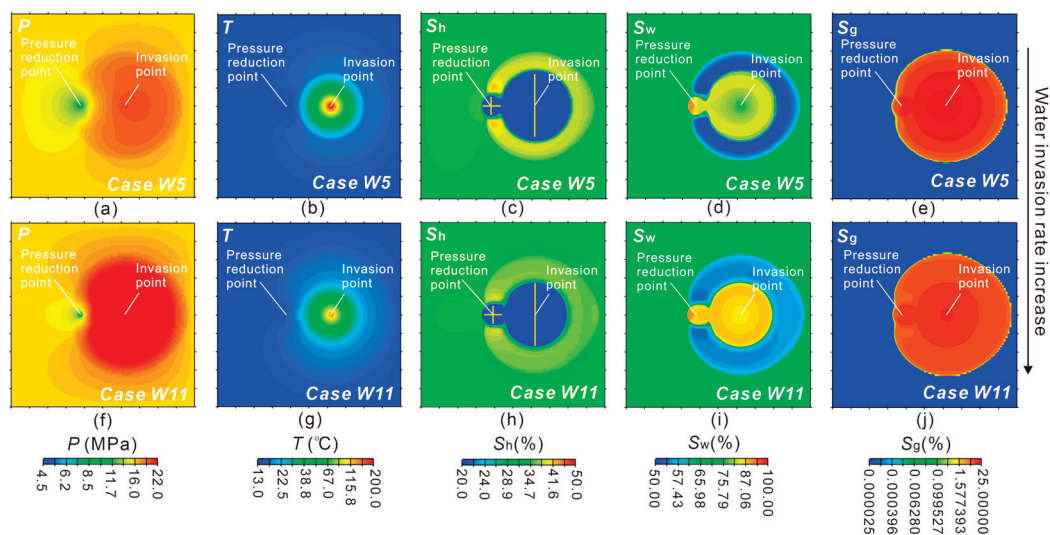


Figure 9. Comparison of physical fields between Cases W5 (water invasion rate of 1.00×10^{-4} kg/s) and W11 (water invasion rate of 1.40×10^{-3} kg/s) at $t = 360$ days. (a) Case W5: pressure, (b) Case W5: temperature, (c) Case W5: hydrate saturation, (d) Case W5: water saturation, (e) Case W5: gas saturation, (f) Case W11: pressure, (g) Case W11: temperature, (h) Case W11: hydrate saturation, (i) Case W11: water saturation, and (j) Case W11: gas saturation. To quantitatively compare the spatial extent of hydrate dissociation between figures (c,h), equidistant yellow lines were employed.

High water invasion rates reduce gas production due to several factors. At low water invasion rates, weak connectivity between the pressure reduction front and the invasion zone limits gas–water pathways, allowing methane to migrate more easily than water, resulting in high methane and low water saturation near the front (Figure 9c–e). In contrast, high water invasion improves connectivity, enhancing water influx and increasing water saturation and production (Figure 9h,i). Additionally, greater water invasion lowers gas fugacity and forms a protective water layer over hydrates, reducing gas diffusion and transfer rates [38–40]. Therefore, higher water invasion rates significantly reduce gas production.

3.2.2. Effect of Methane Invasion Rate

Comparing Cases M1~M18 with Cases 1 and 2 shows that methane invasion rates significantly affect gas production, water production, and gas-to-water ratio (Figure 10a–c). Specifically, higher methane invasion rates lead to greater gas production and gas-to-water ratios, with the onset of significant production enhancement occurring earlier for larger invasion rates (Figure 10a,c). For lower methane invasion rates (Cases M1~M10, 1.00×10^{-6} – 1.80×10^{-5} kg/s), significant gas production enhancement occurs around at $t = 133$ – 140 days; for moderate methane invasion rates (Cases M11~M14, 1.00×10^{-4} – 1.80×10^{-4} kg/s), it occurs between 88 and 106 days; and for higher methane invasion rates (Cases M15~M18, 1.00×10^{-3} – 1.60×10^{-3} kg/s), it occurs between 31 and 41 days (Table S2 in the Supplementary Material). As shown in the comparative analysis of water production rates between Case 1 and other cases (Figure 10b), when the methane invasion rate exceeds 1.80×10^{-5} kg/s (Case M10), the pressure reduction point maintains significantly lower water production rates than Case 1 over an extended period ($t = 150$ – 270 days). Higher methane invasion rates not only trigger earlier suppression of water production but also extend the duration of this inhibitory effect, demonstrating a clear timing-dependent relationship between methane invasion rate and water production behavior.

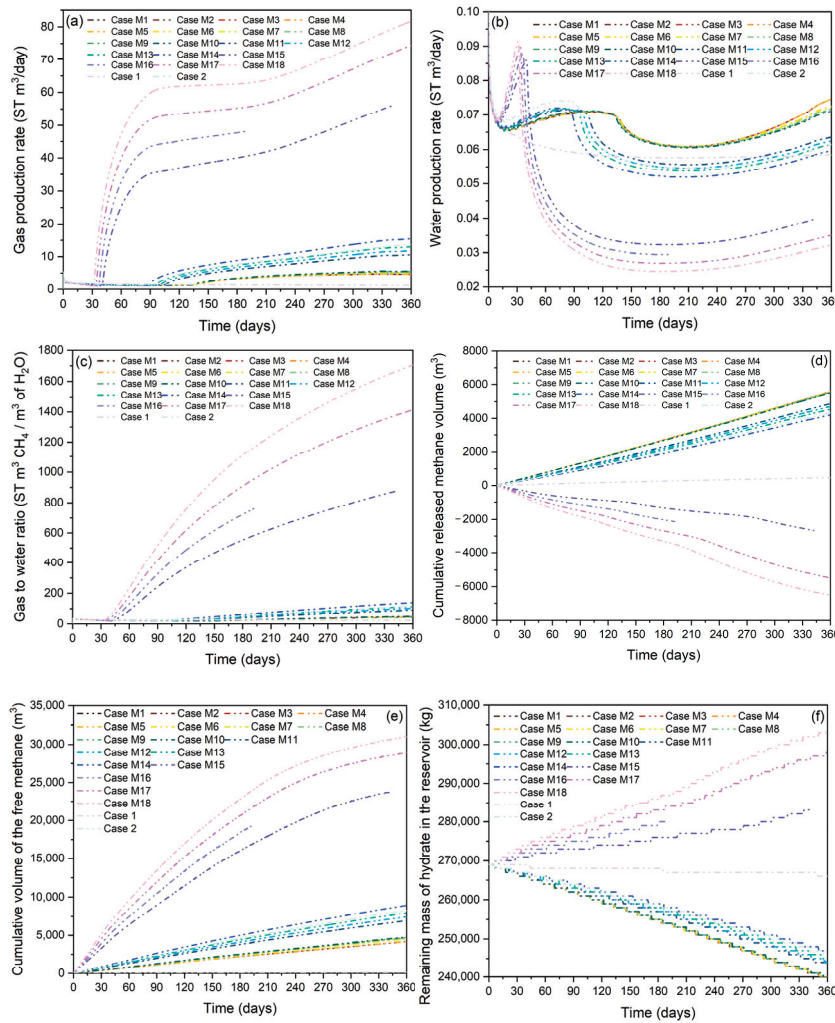


Figure 10. Evolution of (a) gas production rate (m^3/day) at the pressure reduction point, (b) water production rate (m^3/day) at the pressure reduction point, (c) gas-to-water ratio at the pressure reduction point, (d) cumulative released methane volume (m^3), (e) cumulative volume of the free methane (m^3) and (f) remaining mass of hydrate in the reservoir (kg) for Cases 1, 2, and M1~M18.

Regardless of the methane invasion rate, the cumulative volume of free methane in Cases M1~M18 and Case 2 consistently exceeds that in Case 1 (Figure 10e) and shows a positive correlation with the methane invasion rate. However, the cumulative volume of released methane decreases as the methane invasion rate increases (Figure 10d). Notably, when the methane invasion rate exceeds 1.00×10^{-3} kg/s (as in Case M15), hydrate-derived gas production becomes negative. Meanwhile, the remaining hydrate mass in the reservoir increases with higher methane invasion rates (Figure 10f).

As discussed above, high methane invasion rates enhance gas output. When the invasion rate is below 1.00×10^{-3} kg/s (e.g., Cases M10 and M11), methane experiences lower flow resistance than water in the hydrate-bearing reservoir. This allows both invading and dissociated methane to migrate easily to the depressurization front, as supported by the lower water saturation near the pressure reduction point under high invasion rates (Figure 11d,i). When the invasion rate exceeds 1.00×10^{-3} kg/s (Case M18), secondary hydrate forms and narrows the high-permeability zone. Despite this, methane can still reach the pressure reduction point through narrow pathways, sustaining higher gas production.

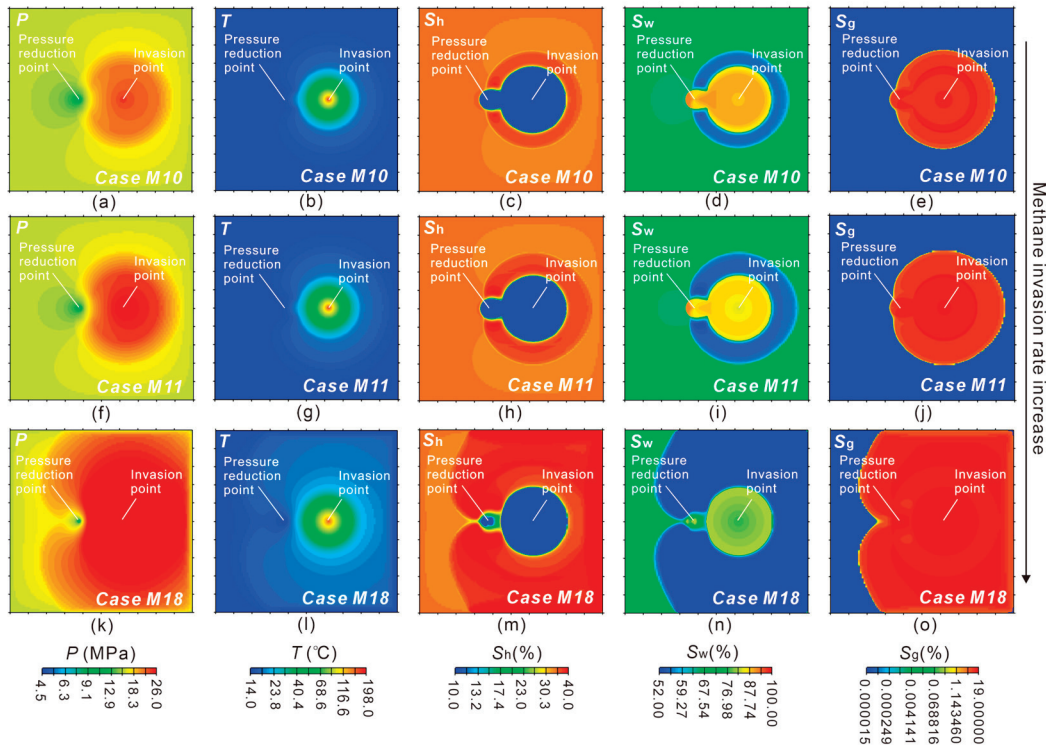


Figure 11. Comparison of physical fields between Case M10 (methane invasion rate of 1.80×10^{-5} kg/s), Case M11 (methane invasion rate of 1.00×10^{-4} kg/s), and Case M18 (methane invasion rate of 1.60×10^{-3} kg/s) at $t = 360$ days. (a) Case M10: pressure, (b) Case M10: temperature, (c) Case M10: hydrate saturation, (d) Case M10: water saturation, (e) Case M10: gas saturation, (f) Case M11: pressure, (g) Case M11: temperature, (h) Case M11: hydrate saturation, (i) Case M11: water saturation, and (j) Case M11: gas saturation, (k) Case M18: pressure, (l) Case M18: temperature, (m) Case M18: hydrate saturation, (n) Case M18: water saturation, and (o) Case M18: gas saturation.

High methane flux inhibits hydrate dissociation while promoting external methane accumulation in reservoir pores. Excessive methane input may trigger secondary hydrate formation exceeding the dissociation amount (Figure 10d–f). This results from a pressure rise near the invasion point with increasing methane injection (Figure 11). Under high-pressure conditions, secondary hydrate forms at the outer edge of the dissociation zone around the methane-rich fluid invasion point, with higher injection rates causing more extensive formation. When the methane invasion rate exceeds 1.00×10^{-3} kg/s

(Case M18), methane cannot be produced efficiently, leading to secondary hydrate near the pressure reduction front (Figure 11m). Over time, dissociation near the fluid invasion point stabilizes, while dissociation near the pressure reduction point decreases with increasing methane invasion. Additionally, high-temperature methane increases gas fugacity in the reservoir pores, which weakens the diffusion of gas through the liquid film surrounding the hydrates and thus inhibits hydrate dissociation. Although the liquid film thins under high temperature, it still impedes gas diffusion, further reducing the driving force for dissociation [24]. Collectively, these effects reduce hydrate dissociation under high methane invasion compared to low rates.

3.2.3. Effect of Heat Supply Rate

Except for Cases H1~H4 and Case 2 (Figure 12, with a heat supply rate of 1.00×10^3 to 1.80×10^3 W), the other cases did not converge and are not discussed in detail in this section.

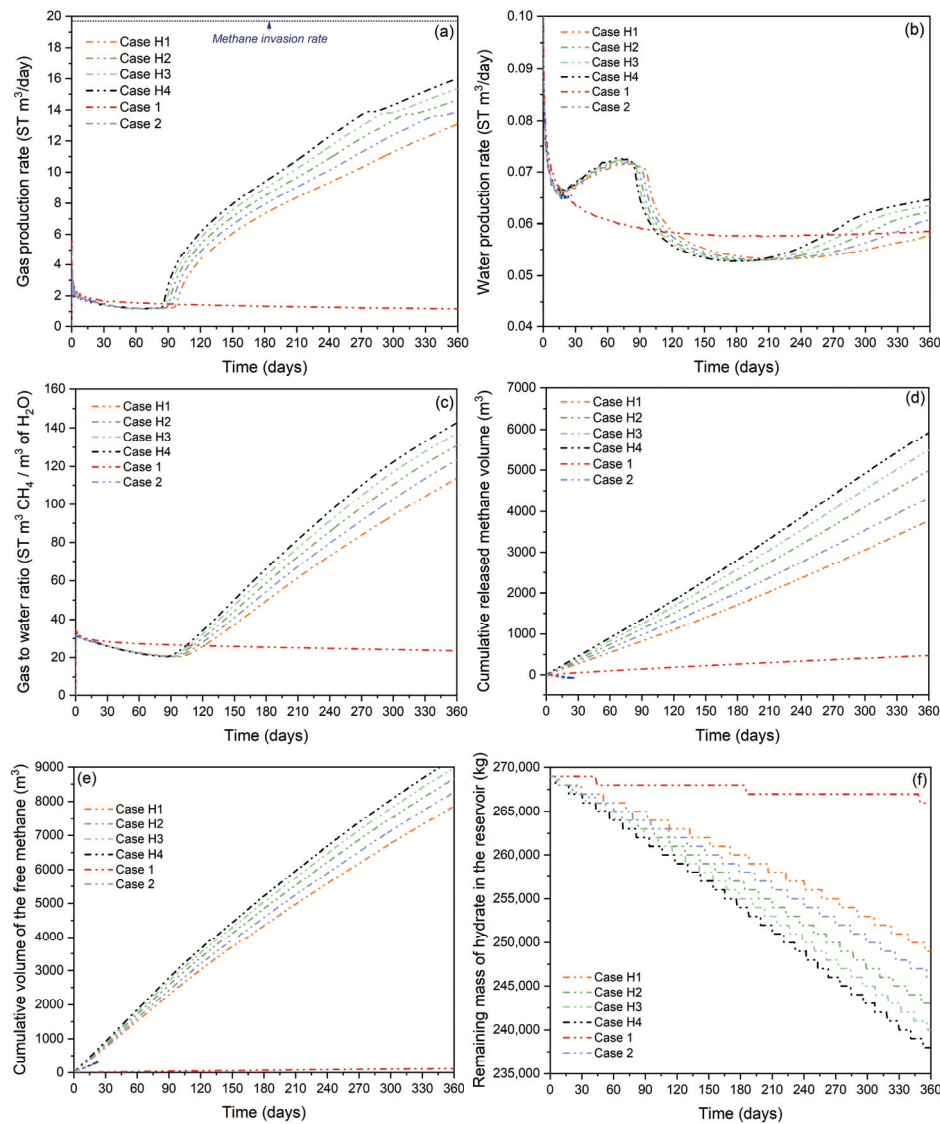


Figure 12. Evolution of (a) gas production rate (m³/day) at the pressure reduction point, (b) water production rate (m³/day) at the pressure reduction point, (c) gas-to-water ratio at the pressure reduction point, (d) cumulative released methane volume (m³), (e) cumulative volume of the free methane (m³) and (f) remaining mass of hydrate in the reservoir (kg) for Cases 1, 2, and H1~H4.

Comparative analysis of Cases H1~H4 and Case 2 shows that the heat supply rate significantly influences the gas production rate, water production rate, and gas-to-water ratio at the pressure reduction point (Figure 12a–c). All these cases exhibit consistent evolutionary trends for these parameters, but the trends differ distinctly from those in Case 1. As shown in Figure 12a, before the gas production rates in Cases H1~H4 exceed those in Case 1, gas production is relatively insensitive to the heat supply rate. Around $t = 85\text{--}98$ days, the gas production rate begins to increase with higher heat supply rates, which trigger an earlier onset of significant enhancement (Table S2 in the Supplementary Material). The water production rate first remains nearly unchanged, then increases, decreases, and finally rises again with increasing heat supply rate (Figure 12b). For the gas-to-water ratio, sensitivity to heat supply rate is low before $t = 104\text{--}122$ days, but after this period, higher heat supply rates lead to earlier and more pronounced increases (Figure 12c).

As shown in Figure 9d,e, the cumulative released methane volume and free methane in the reservoir for Cases H1~H4 and 2 exceed those in Case 1 and increase with rising heat supply rate. Meanwhile, the remaining hydrate in the reservoir for these cases is significantly lower than in Case 1 and decreases further as the heat supply rate increases (Figure 12f).

As mentioned above, higher heat supply rates at the methane-rich fluid invasion point enhance hydrate dissociation and gas production. This thermal stimulation creates a positive feedback by increasing pressure and temperature near the invasion zone (Figure 13a,b,f,g), promoting secondary hydrate formation and expanding the hydrate dissociation extent (Figure 13c,h). Under identical methane and water invasion, greater hydrate dissociation leads to higher methane accumulation and expands gas–water migration pathways, significantly increasing methane flux toward the pressure reduction point (Figure 13j).

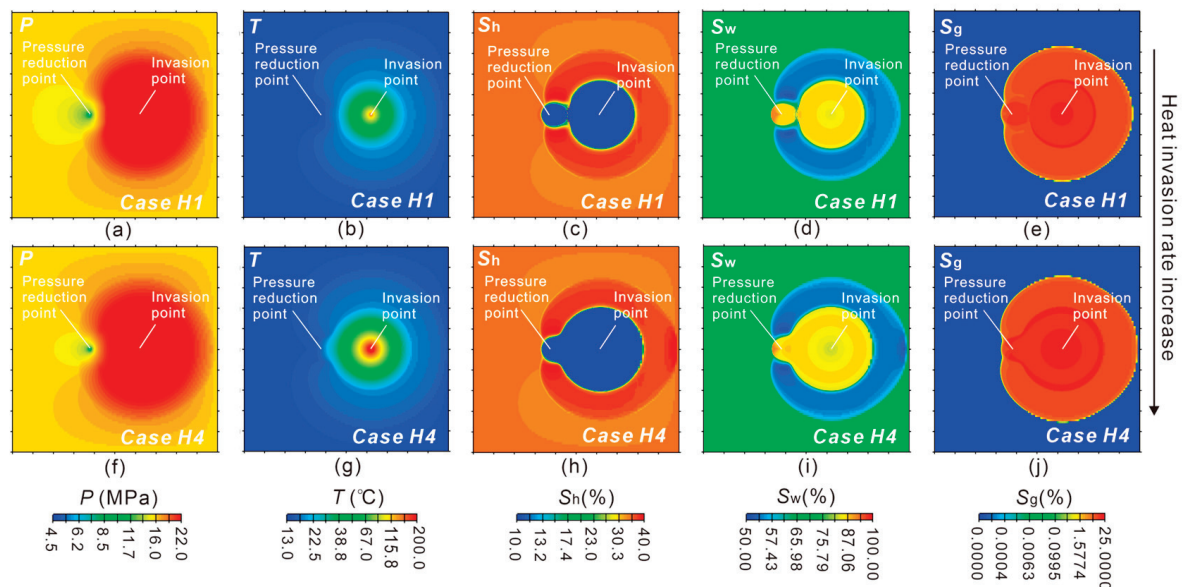


Figure 13. Comparison of physical fields between Cases H1 (heat supply of 1.00×10^3 W) and H4 (heat supply of 1.80×10^3 W) at $t = 360$ days. (a) Case H1: pressure, (b) Case H1: temperature, (c) Case H1: hydrate saturation, (d) Case H1: water saturation, (e) Case H1: gas saturation, (f) Case H4: pressure, (g) Case H4: temperature, (h) Case H4: hydrate saturation, (i) Case H4: water saturation, and (j) Case H4: gas saturation.

3.3. Synergistic Enhancement of Gas Production by Methane-Rich Fluid Invasion ("1 + 1 > 2" Effect)

Figure 8a compares gas production rates at the pressure reduction point versus methane invasion rates under different water invasion rates. The results show that when the water invasion rate is below 2.00×10^{-4} kg/s (Case W6), the gas production rate exceeds the methane invasion rate (1.54×10^{-4} kg/s), and as the water invasion rate decreases, this crossover occurs at an earlier stage. Table S3 in the Supplementary Material shows that when the methane invasion rate is below 1.80×10^{-5} kg/s (Case M10), the actual gas production rate also exceeds the methane invasion rate. Notably, this phenomenon presents since the invasion of methane-rich fluids into the reservoir. In contrast, Figure 12a demonstrates that varying the heat supply rate alone does not enable the actual gas production rate to surpass the methane invasion rate.

To evaluate the potential enhancement effect of methane-rich fluid invasion, we compare the actually measured gas production during fluid invasion with the theoretical gas production (sum of injected methane and hydrate-derived gas under conditions without methane-rich fluid invasion). Both values are evaluated over the same pressure reduction period for accurate comparison, using $t = 360$ days as a representative case. When the measured production exceeds the theoretical value, it confirms that methane-rich fluid invasion enhances hydrate reservoir gas production, demonstrating a synergistic "1 + 1 > 2" effect.

As illustrated in Figure 14, the actual gas production rate consistently remains below theoretical values under high-temperature methane-rich fluid invasion, regardless of heat supply rate variations (Figure 14c). In contrast, when water or methane invasion rates are maintained at low invasion rates, the actual production rates exceed theoretical values (Figure 14a,b), demonstrating a distinct "1 + 1 > 2" synergistic effect where fluid invasion significantly enhances gas production. Under optimal conditions, the actual gas production rate achieves a 3.76-fold increase over the theoretical value, with overall gas production capacity showing a 4.29-fold enhancement compared to non-invasion scenarios. However, progressive increases in water or methane invasion rates eventually reverse this trend, causing actual production rates to fall below theoretical values. Higher invasion rates lead to greater discrepancies between actual and theoretical values. This phenomenon is primarily related to the gas production rate decreases with increasing water invasion rate (Figure 8a), and higher methane invasion rates promote methane retention within the reservoir and enhance hydrate formation (Figure 10f).

This study employs a conceptual two-dimensional model to simulate the coupled processes of well depressurization and methane-rich fluid invasion in gas hydrate reservoirs. Although the representation of high-permeability conduits is simplified, it enables direct fluid invasion and provides insights into fluid-hydrate interactions. The model domain is small and the vertical thickness defines a computational layer only, with constant-temperature, impermeable lateral boundaries. Consequently, absolute gas and water production values are indicative rather than predictive, and long-term or high-intensity fluid injection may cause pressure disturbances at the boundaries. The model reflects the evolution of a single well or representative unit and cannot directly represent large-scale reservoirs or well-field systems. Despite these limitations, the model reliably captures relative trends in hydrate dissociation, gas and water production, and the effects of fluid invasion, making it suitable primarily as a conceptual tool for mechanism exploration.

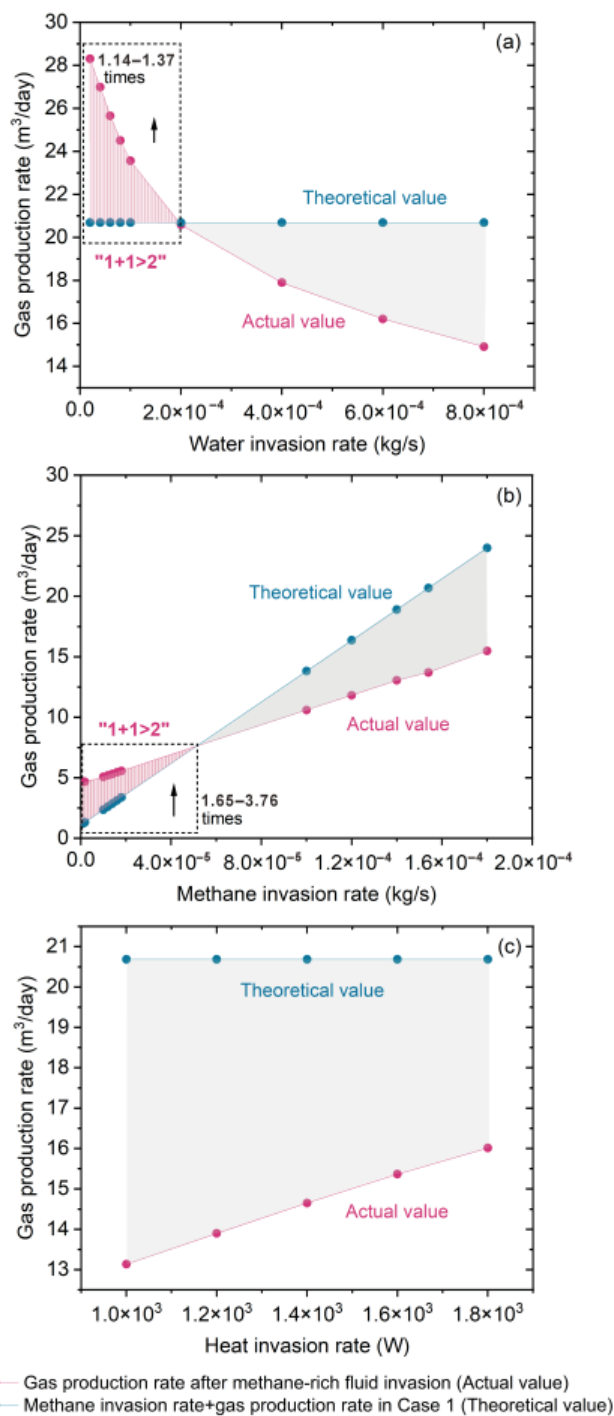


Figure 14. Comparison of actual gas production rates in Cases W1–W12, M1–M18, H1–H4, and Case 2 under methane-rich fluid invasion (actual value, m³/day) with the theoretical values (sum of methane invasion rate and gas production rate in Case 1) at $t = 360$ days. (a) Gas production rate for different water invasion rates, (b) gas production rate for different methane invasion rates, and (c) gas production rate for different heat invasion rates.

4. Conclusions and Outlook

The main findings and future perspectives of this study are summarized as follows:

- (1) The invasion of methane-rich fluid into gas hydrate systems exhibits a three-phase impact on gas production dynamics. In the initial stage, the invasion shows no significant effect. After a certain period, it begins to enhance hydrate dissociation but temporarily inhibits gas production. Under sustained invasion, it significantly

promotes hydrate dissociation and increases gas production. Future studies should focus on quantifying the critical transition thresholds between the inhibition and promotion phases of gas production under field-scale conditions; this is essential for optimizing depressurization strategies and improving production efficiency.

- (2) Low water invasion and elevated heat supply enhance hydrate dissociation and promote gas production. In contrast, high methane flux reduces hydrate dissociation and increases external methane accumulation in reservoir pores. Notably, excessive methane input may lead to the formation of new hydrate exceeding the amount of dissociated hydrate in the reservoir. Therefore, in future field development site selection, priority should be given to fluid conduit-associated gas hydrate systems characterized by high methane flux, high heat flux, and low water invasion rates, as these conditions are more favorable for efficient and stable gas recovery.
- (3) When the actual gas production exceeds the theoretical value, it confirms that methane-rich fluid invasion enhances hydrate-reservoir gas production, exhibiting a synergistic “ $1 + 1 > 2$ ” effect, particularly at low water or methane invasion rates. Controlled methane-rich fluid injection at optimally low rates may serve as an effective stimulation technique to enhance gas recovery while maintaining reservoir stability. Future studies should focus on the coupled effects of methane and water invasion under depressurization to determine optimal invasion rate combinations for maximizing the synergistic enhancement. Establishing quantitative criteria to identify the onset and intensity of this effect will be crucial for guiding real-time production control and intelligent operation strategies. Additionally, developing advanced monitoring and control technologies to regulate multiphase fluid fluxes, together with long-term assessments of reservoir stability and environmental safety, will support adaptive, high-efficiency, and environmentally sustainable gas production strategies in the SCS and other continental margins.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/jmse13112166/s1>. Figure S1. Evolution of reservoir properties in Case 1 (35 m $\times$ 30 m): (a) pressure (P), (b) temperature (T), (c) hydrate saturation (S_h), (d) gas saturation (S_g), and (e) water saturation (S_w). Figure S2. Spatial distributions of (a) gas saturation (S_g) and (b) water saturation (S_w) at $t = 10$ days for Case 2 (30 m $\times$ 10 m). Figure S3. Reservoir physical field distributions for (a) Case 1 and (b) Case 2 at $t = 30$ days (50 m $\times$ 50 m). Table S1. Cases setup. Figure S4. Evolution of (a) gas production rate, (b) water production rate, (c) gas-to-water ratio, (d) cumulative volume of the released gas, (e) cumulative volume of the free gas in the domain, and (f) remaining mass of hydrate in the reservoir for Cases 1, a, and a-1~a-9. Figure S5. Evolution of (a) gas production rate, (b) water production rate, (c) gas-to-water ratio, (d) cumulative volume of the released gas, (e) cumulative volume of the free gas in the domain, and (f) remaining mass of hydrate in the reservoir for Cases 1, b, and b-1~b-18. Figure S6. Evolution of (a) gas production rate, (b) water production rate, (c) gas-to-water ratio, (d) cumulative volume of the released gas, (e) cumulative volume of the free gas in the domain, and (f) remaining mass of hydrate in the reservoir for Cases 1, c, and c-1~c-10. Table S2. Times at which the gas production rate significantly increases and exceeds that of Case 1 under different water, methane, and heat input rates. Table S3. Methane invasion rate and actual gas production rate at $t = 360$ day in Cases M1~M18 and Case 2.

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Abbreviations

The following abbreviations are used in this manuscript:

SCS	South China Sea
H ₂ O	Water
CH ₄	Methane
MTD	Mass transport deposit
HAR	High amplitude reflection
GHSZ	Gas hydrate stability zone
BGHSZ	Base of gas hydrate stability zone
BSR	Bottom-simulating reflections
PRMB	Pearl River Mouth Basin
QDNB	Qiongdongnan Basin
FII	Fault
SW	Southwest
NE	Northeast

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Article

Remaining Useful Life Prediction and Operation Optimization of Offshore Electric Submersible Pump Systems Using a Dual-Stage Attention-Based Recurrent Neural Network

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Abstract

Electric Submersible Pumps (ESPs) serve as the primary artificial lift technology in offshore oilfields and play a crucial role in ensuring stable and efficient marine oil and gas production. However, the harsh offshore operating environment—characterized by high temperature, complex multiphase flow, and frequent load fluctuations—makes ESPs highly susceptible to accelerated degradation and unexpected failure. To enhance the operational reliability and efficiency of offshore production systems, this study develops a Remaining Useful Life (RUL) prediction method for offshore ESP systems using a Dual-Stage Attention-Based Recurrent Neural Network (DA-RNN). The model integrates an input-attention mechanism to identify degradation-relevant offshore operating variables and a temporal-attention mechanism to capture long-term deterioration patterns in real marine production data. Using field data from a representative offshore oilfield in the Bohai Sea, the proposed method achieves an average prediction error of less than 28 days, demonstrating strong robustness under complex offshore conditions. Beyond prediction, an RUL-driven operation optimization strategy is formulated to guide controllable parameters—such as pump frequency and nozzle size—toward extending ESP lifespan and improving offshore production stability. The results show that combining predictive maintenance with operational optimization provides a practical and data-driven pathway for improving the safety, efficiency, and sustainability of offshore oil and gas development. This work aligns closely with the goals of marine resource development and offers a valuable engineering perspective for advancing offshore oilfield operations.

Keywords: electric submersible pump; remaining useful life; DA-RNN; predictive maintenance; operation optimization

1. Introduction

Electric Submersible Pump (ESP) systems are among the most widely used artificial lift technologies in offshore oilfields [1]. By deploying a multistage centrifugal pump and a downhole motor into the well and delivering electrical power from the surface, ESPs provide high production rates and a high degree of automation. Globally, 15–20% of producing wells rely on ESPs [2]; these wells account for nearly 60% [3] of world oil production.

However, continuous operation in environments characterized by high temperature, mechanical loading, and complex multiphase flow conditions makes ESPs highly susceptible to degradation and failure. Their operation and maintenance represent approximately 43% of global artificial-lift expenditure [4]; any failure may result in substantial workover costs and prolonged production shutdowns [5,6].

Remaining Useful Life (RUL) prediction for complex industrial equipment has been extensively studied, with approaches largely divided into physics-based models and data-driven models. Physics-based models describe degradation mechanisms through explicit mathematical formulations, such as crack-growth laws [7–9], small-crack fatigue theories [10,11], and energy-based fatigue life models [12,13], offering strong interpretability. However, for ESP systems, which feature multistage structures, nonlinear couplings, and diverse operating conditions, the construction of accurate mechanistic models remains extremely challenging. Data-driven methods have gained momentum with the advancement of digital oilfield technologies, enabling degradation behaviors to be learned directly from large-scale monitoring data without the need for detailed prior knowledge [14–17]. Nonetheless, these approaches still face key limitations, including weak adaptive feature selection, insufficient modeling of long-term temporal dependencies, limited generalization across varying operating conditions, and unstable uncertainty representation.

More critically, most existing studies focus on predicting the remaining life of equipment, while research on how to utilize these predictions to guide operational adjustments, mitigate degradation, and extend system lifespan remains scarce. In practice, field operations require not only an estimate of how long an ESP can continue running, but also actionable insights into how the system should be operated to make it run longer. Current studies in the literature provide limited guidance on how controllable parameters—such as operating frequency or choke settings—can be systematically optimized to slow degradation and enhance equipment longevity. This gap highlights an urgent need for frameworks that integrate lifespan prediction with lifespan-oriented operational decision-making.

The Dual-Stage Attention-based Recurrent Neural Network (DA-RNN) provides a promising pathway to address these challenges. Its input attention mechanism adaptively identifies the most degradation-relevant features, while its temporal attention mechanism highlights critical moments in the evolution of system degradation. This architecture not only improves prediction accuracy for multivariate time-series data but also offers interpretable insights into how different operating variables contribute to degradation progression. Such interpretability forms an essential foundation for translating predictive information into operational strategies, enabling the transition from pure lifespan prediction to actionable lifespan optimization. The DA-RNN provides a promising pathway to address these challenges. The DA-RNN was originally proposed for time series prediction, combining an input attention mechanism that adaptively identifies the most relevant driving series with a temporal attention mechanism that highlights critical hidden states over time [18]. Building on the encoder–decoder paradigm and long short-term memory (LSTM) [19] units for capturing long-range dependencies, attention-based recurrent architectures have demonstrated strong capabilities in modeling complex, multivariate temporal dynamics and extracting interpretable feature importance patterns [20,21]. Such interpretability is particularly valuable for industrial prognostics, as it reveals how different operating variables contribute to degradation progression and provides a principled basis for connecting RUL prediction with maintenance and operation decisions [22].

Building upon these considerations, this study develops an integrated framework for RUL prediction and operation optimization of ESP systems. While existing attention-based RUL prediction models mainly focus on enhancing prediction accuracy, the present framework extends RUL modeling toward operation-relevant analysis by explicitly inte-

grating prediction results with operating-regime adjustment. A dual-stage attention-based recurrent neural network is employed to extract degradation-related features from multi-source time-series data and to generate accurate RUL predictions under complex offshore operating conditions. Based on the predicted RUL trajectories and the analysis of operating-parameter effects, an operation optimization strategy is further formulated to support lifespan-oriented adjustment of ESP operating regimes. Field data validation demonstrates that the proposed framework can effectively capture degradation trends and provide data-driven support for improving ESP reliability, operational safety, and maintenance decision-making.

The main contributions of this study are summarized as follows:

- (1) An integrated framework is developed for RUL prediction and operation optimization of ESP systems, enabling degradation assessment and operating-regime adjustment to be addressed in a unified manner;
- (2) A dual-stage attention-based recurrent neural network is employed not only to improve RUL prediction accuracy, but also to provide operationally meaningful interpretation of the influence of controllable operating variables on degradation evolution;
- (3) An RUL-driven operation optimization strategy is proposed, in which predicted lifespan trajectories are embedded into an operation optimization process to guide lifespan-oriented adjustment of operating parameters, thereby enhancing the practical applicability of data-driven prognostics in offshore ESP management.

2. Theoretical Foundation

2.1. Remaining Useful Life of ESP Systems

The RUL of an Electric Submersible Pump system refers to the amount of time the system can continue to operate normally under its current health condition. The formal definition of RUL is given by [23]:

$$T_{\text{RUL}}(t) = t_f - t_c, t_f \geq t_c \quad (1)$$

where $T_{\text{RUL}}(t)$ denotes the remaining lifetime of the ESP system at time t , measured in days, t_f represents the failure time, and t_c denotes the current operating time. In this study, an ESP failure is defined as a condition in which the pump system is retrieved from the well due to confirmed functional loss or severe degradation such as motor burnout, electrical insulation failure, mechanical seizure, or other faults identified through field diagnosis and post-retrieval inspection. The failure time t_f is labeled based on actual field records, including workover reports and maintenance logs, which document the date of pump retrieval and confirmed failure events. Reliable RUL prediction enables proactive scheduling of preventive maintenance, reduces the probability of unexpected failures, and minimizes production downtime, ultimately improving the safety, reliability, and economic efficiency of ESP operations.

However, field operation records indicate that not all ESP retrieval events correspond to actual failures. Early pull-outs performed for preventive inspection, operational adjustment, or surface facility maintenance, as well as non-failure shutdowns caused by production planning or external constraints, are treated as censored cases in this study. Since reliable failure times cannot be defined for these events, such samples are excluded from the supervised RUL model training and evaluation. Only ESP instances with confirmed failure events and clearly documented failure times are retained to ensure the consistency and physical validity of the RUL labels. Accordingly, the RUL ground truth in this study is constructed as the time interval between the current operating time and the confirmed failure time for each retained ESP instance.

2.2. Dual-Stage Attention-Based Recurrent Neural Network (DA-RNN)

The DA-RNN is a neural architecture designed for time series prediction tasks. By integrating attention mechanisms with recurrent neural networks, DA-RNN enhances the ability to identify and extract informative patterns from multivariate input data. The network consists of an encoder and a decoder, each equipped with its own attention module.

The input-attention mechanism introduced in the encoder assigns adaptive importance weights to different driving sequences, while the temporal-attention mechanism in the decoder evaluates the relevance of encoder hidden states over time. Together, these two modules enable simultaneous feature-level and temporal-level selection within a unified encoder–decoder framework, allowing DA-RNN to extract degradation-relevant patterns from multivariate ESP operating data. The overall architecture of DA-RNN is shown in Figure 1.

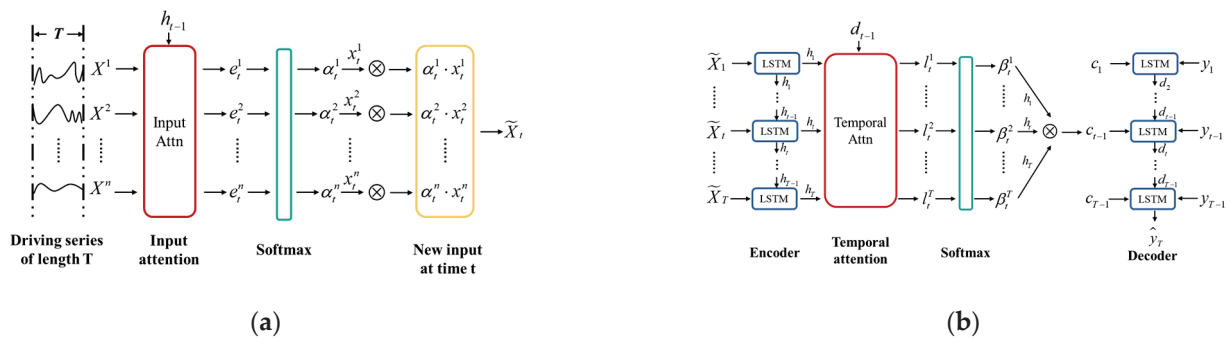


Figure 1. Architecture of the DA-RNN model for ESP RUL prediction: (a) input attention module, which dynamically assigns weights to multivariate operating variables at each time step, highlighting features that are most relevant to equipment degradation; and (b) temporal attention module, which selectively emphasizes critical historical time steps in the hidden-state sequence, enabling the model to focus on key degradation-related temporal patterns. Together, the dual-stage attention mechanism enhances both interpretability and prediction accuracy.

The encoder is essentially a recurrent neural network (RNN) designed to map an input multivariate time series into a sequence of latent representations. For a time step t , the encoder updates its hidden state $h_t \in \mathbb{R}^m$ according to:

$$h_t = f_1(h_{t-1}, X_t) \quad (2)$$

where m denotes the dimensionality of the hidden state, and $f_1(\cdot)$ represents a nonlinear state-transition function. In this study, the long short-term memory (LSTM) architecture is adopted due to its capability to mitigate gradient vanishing and capture long-term temporal dependencies inherent in the degradation processes of ESP systems. Given an RUL-related feature sequence $X = (x_1, x_2, \dots, x_T)$, where $x_t \in \mathbb{R}^n$ and T is the total number of time steps, the update equations of an LSTM cell are expressed as:

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f) \quad (3)$$

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \quad (4)$$

$$\tilde{s}_t = \tanh(W_s \cdot [h_{t-1}, x_t] + b_s) \quad (5)$$

$$s_t = f_t \odot s_{t-1} + i_t \odot \tilde{s}_t \quad (6)$$

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \quad (7)$$

$$h_t = o_t \odot \tanh(s_t) \quad (8)$$

where $\sigma(\cdot)$ denotes the sigmoid function; W_f, W_i, W_s, W_o and b_f, b_i, b_s, b_o are the trainable weight matrices and bias terms; f_t, i_t , and o_t correspond to the forget, input, and output gates; $\tilde{s}_t$ is the candidate cell state; and s_t is the internal memory cell that propagates long-term information. To enable the encoder to automatically identify the most degradation-sensitive features, an input attention mechanism is incorporated. For the k -th feature at time step t , an alignment score is computed as:

$$e_t^k = V_e^T \tanh(W_e[h_{t-1}, s_{t-1}] + U_e X^k) \quad (9)$$

which is normalized through a softmax function to obtain the attention weight:

$$\alpha_t^k = \frac{\exp(e_t^k)}{\sum_{i=1}^n \exp(e_t^i)} \quad (10)$$

This input attention mechanism acts as a feature-level gating network that trains jointly with the rest of the DA-RNN model. It adaptively assigns higher weights to features highly correlated with ESP degradation—such as electrical load, operating pressure, or thermal stress—while suppressing noisy or weakly relevant measurements. The refined input vector is given by:

$$\tilde{X}_t = (\alpha_t^1 x_t^1, \alpha_t^2 x_t^2, \dots, \alpha_t^n x_t^n)^T \quad (11)$$

which is subsequently used in the LSTM update:

$$h_t = f_1(h_{t-1}, \tilde{X}_t) \quad (12)$$

By integrating attention-weighted inputs into the recurrent update, the encoder is able to focus selectively on degradation-relevant temporal patterns while filtering out irrelevant fluctuations. This design substantially enhances the ability of DA-RNN to extract robust and interpretable degradation features from multivariate ESP monitoring data, thereby strengthening the foundation for accurate RUL prediction.

In the decoder, an LSTM unit is employed to process the sequence of hidden states generated by the encoder and produce the prediction $\hat{y}_t$, representing the RUL of the ESP system at time t . However, as the input sequence length increases, the performance of conventional encoder–decoder architectures tends to degrade because the decoder is unable to fully exploit all historical information. To address this limitation, a temporal attention mechanism is integrated into the decoder, enabling it to adaptively identify the encoder hidden states that contribute most to the current prediction.

To compute the temporal attention, an alignment score is first constructed using the previous decoder hidden state d_{t-1} , the previous decoder cell state s_{t-1} , and the encoder hidden state at time step i , denoted by h_i . This alignment score is calculated by a feed-forward neural network and reflects the relevance between the encoder state at time i and the current prediction task. The computation is given by:

$$l_t^i = V_d^T \tanh(W_d[d_{t-1}, s_{t-1}] + U_d h_i) \quad (13)$$

where V_d, W_d , and U_d are learnable parameters. The use of both d_{t-1} and s_{t-1} is essential: while d_{t-1} captures short-term temporal variations, the cell state s_{t-1} stores long-term degradation trends such as gradual increases in motor temperature or load. By combining these two types of information, the alignment score can more accurately determine the importance of each past time step. Normalization via softmax yields the attention weights:

$$\beta_t^i = \frac{\exp(l_t^i)}{\sum_{j=1}^T \exp(l_t^j)} \quad (14)$$

The temporal attention weights are then used to construct a context vector c_t , which is a weighted sum of all encoder hidden states:

$$c_t = \sum_{i=1}^T \beta_t^i h_i \quad (15)$$

The context vector serves as a condensed representation of the historical information most relevant to the current prediction, enabling the decoder to selectively emphasize key moments in the degradation process rather than relying solely on the final encoder output. After obtaining the context vector, the decoder concatenates it with the previous target value y_{t-1} and applies a linear transformation to obtain the decoder input:

$$\tilde{y}_t = F([y_{t-1}, c_t]) \quad (16)$$

where $F(\cdot)$ is a trainable mapping. The LSTM unit then updates its hidden state based on this input:

$$d_t = f_2(d_{t-1}, \tilde{y}_t) \quad (17)$$

where $f_2(\cdot)$ follows the same update equations as the LSTM described earlier. Finally, the predicted RUL at time T is obtained by concatenating the decoder hidden state d_T and the context vector c_T and projecting them through a linear layer:

$$\tilde{y}_T = W_y[d_T, c_T] + b_y \quad (18)$$

By incorporating the temporal attention mechanism, the decoder is able to focus on the most informative moments in the historical sequence at each prediction step. This design complements the feature-level screening performed by the encoder and ensures that the predicted RUL is informed by both degradation-sensitive variables and critical temporal stages. As a result, the DA-RNN architecture provides a compact and interpretable representation for modeling the degradation dynamics of ESP systems.

3. Methodology

3.1. Feature Importance Analysis for RUL Prediction

This study analyzes the key factors influencing the RUL of electric submersible pumps using historical data from 712 ESP wells in the Bohai Oilfield. The dataset includes wellhead and downhole sensor measurements, electrical operating parameters, and fluid production variables. Summary statistics of these variables are presented in Table 1. Prior to correlation analysis, the raw data underwent preprocessing, including the removal of outliers beyond physically reasonable limits, imputation of missing values, and normalization of all variables to eliminate the effects of differing units and scales, thereby ensuring a consistent basis for subsequent analysis.

Table 1. Basic overview of ESP wells in the Bohai Oilfield.

No.	Variable Symbol	Influencing Factors	Unit	Minimum	Mean	Maximum
1	V1	Oil pressure	MPa	1.06	2	4.59
2	V2	Casing pressure	MPa	0.69	1.71	4.35
3	V3	Pump inlet pressure	MPa	0.71	3.13	13.32
4	V4	Pump outlet pressure	MPa	1.74	10.82	13.79
5	V5	Pump inlet temperature	°C	40.21	58.83	79.91

Table 1. Cont.

No.	Variable Symbol	Influencing Factors	Unit	Minimum	Mean	Maximum
6	V6	Motor temperature	°C	40.07	89.55	139.29
7	V7	Current	A	15.39	44.52	82.89
8	V8	Voltage	V	609.02	1840.84	2536.1
9	V9	Frequency	Hz	21	49.36	65.67
10	V10	Motor Power	KW	13.87	104.96	250
11	V11	Oil	m ³ /d	0.59	68.21	236.36
12	V12	Gas	10 ⁴ m ³	0.012	0.4	2.75
13	V13	Water	m ³ /d	0.17	237.83	1271.49
14	V14	Liquid	m ³ /d	2.66	306.55	1460.85
15	V15	GOR	m ³ /m ³	1.78	57	331.28

To quantify the relationship between individual variables and RUL, the Pearson correlation coefficient was employed. The coefficient ranges from -1 to 1 , where larger absolute values indicate stronger linear relationships. The Pearson correlation coefficient is computed as:

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (19)$$

where r denotes the correlation coefficient, X_i and Y_i are paired observations of two variables, $\bar{X}$ and $\bar{Y}$ represent their sample means, and n is the number of observations. Based on this formulation, correlations between RUL and 15 candidate variables were calculated and visualized in a heatmap shown in Figure 2. In the heatmap, the horizontal and vertical axes list the variables; the color intensity of each cell reflects the magnitude and direction of the correlation, with blue indicating strong negative correlation and red indicating strong positive correlation.

As shown in Figure 2, current and frequency exhibit the strongest negative correlations with RUL among all variables, highlighting their significant roles in representing the operating conditions and load levels of ESP systems. Moderate correlations are observed for wellhead pressure, pump intake pressure, pump intake temperature, motor temperature, oil production rate, gas production rate, and liquid production rate. These variables contain meaningful degradation-related information and are therefore retained as input features for DA-RNN model training. In this study, variables with absolute Pearson coefficients below 0.2 were excluded, as their weak associations contribute little to degradation modeling and may introduce noise without improving predictive performance.

It should be noted that Pearson correlation analysis was employed here as a preliminary feature screening step rather than a definitive measure of feature importance. The primary purpose of this step was to remove variables with negligible relevance to RUL and reduce input redundancy before model training. The final contribution of each retained feature to RUL prediction was subsequently learned in a data-driven manner by the dual-stage attention mechanism of the DA-RNN, which is capable of capturing nonlinear relationships and time-dependent effects beyond linear correlation. To avoid information leakage, the Pearson correlation-based feature screening was performed using the training dataset only. The selected feature set was then fixed and consistently applied to the testing dataset without further adjustment.

After identifying the variables that exhibit strong relationships with ESP degradation, the next step was to construct an RUL prediction model capable of capturing the temporal degradation patterns embedded in these multivariate operating signals. This

motivated the development of the DA-RNN-based prediction framework described in the subsequent section.

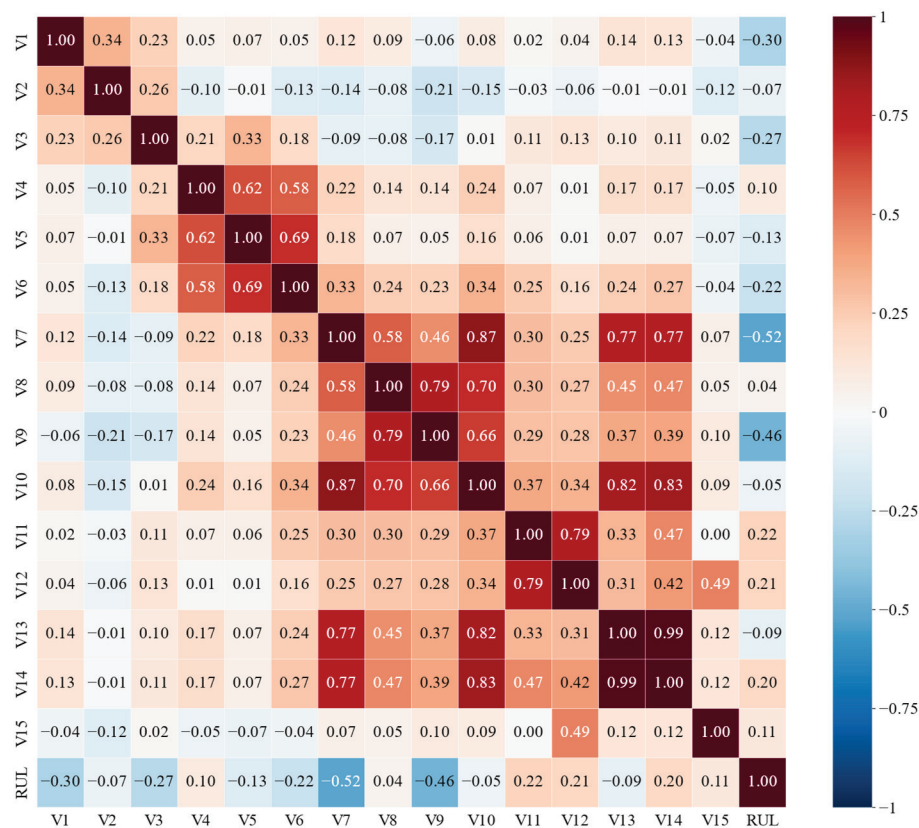


Figure 2. Thermodynamic diagram of Pearson correlation coefficients between candidate operating variables and RUL. The color scale represents the magnitude and sign of the correlation coefficient calculated over the full dataset, with negative values indicating inverse relationships and positive values indicating direct relationships between individual variables and RUL.

3.2. Construction of the DA-RNN-Based RUL Prediction Model

The DA-RNN-based RUL prediction model is illustrated in Figure 3. The modeling process begins with data preprocessing, including normalization and a sliding time-window operation. Normalization eliminates the effects of differing magnitudes across variables and enables the model to focus on temporal variations rather than absolute values. The sliding window divides the continuous time series into fixed-length segments, enabling the model to capture local dynamic behaviors while forming a stable structure suitable for batch training. After windowing, the data are formatted into a three-dimensional tensor representing the feature dimension, window length, and batch size, which preserves the temporal structure of the data and improves computational efficiency during training.

In designing the model inputs and outputs, multivariate features related to operating conditions, load behavior, and fluid characteristics are selected to describe the degradation patterns of the ESP system. The window length is chosen to balance the need to capture short-term dynamics with the requirement of stable model learning. The output is a one-step RUL estimate that advances as the window slides, thereby mimicking the continuous health evolution of the equipment. Ground-truth RUL labels are computed as the difference between the known failure time and the current timestamp and are aligned with the windowed input sequences to maintain temporal consistency during supervised learning. For multivariate time series from different wells, synchronization and alignment are performed only within each individual well based on its own time stamps, with sliding-window segmentation applied independently for each well and no enforced temporal alignment

across wells. To prevent information leakage, the dataset was divided chronologically into 80% for training and 20% for testing, ensuring that the model was always evaluated on data from later operational periods that the network had never seen during training.

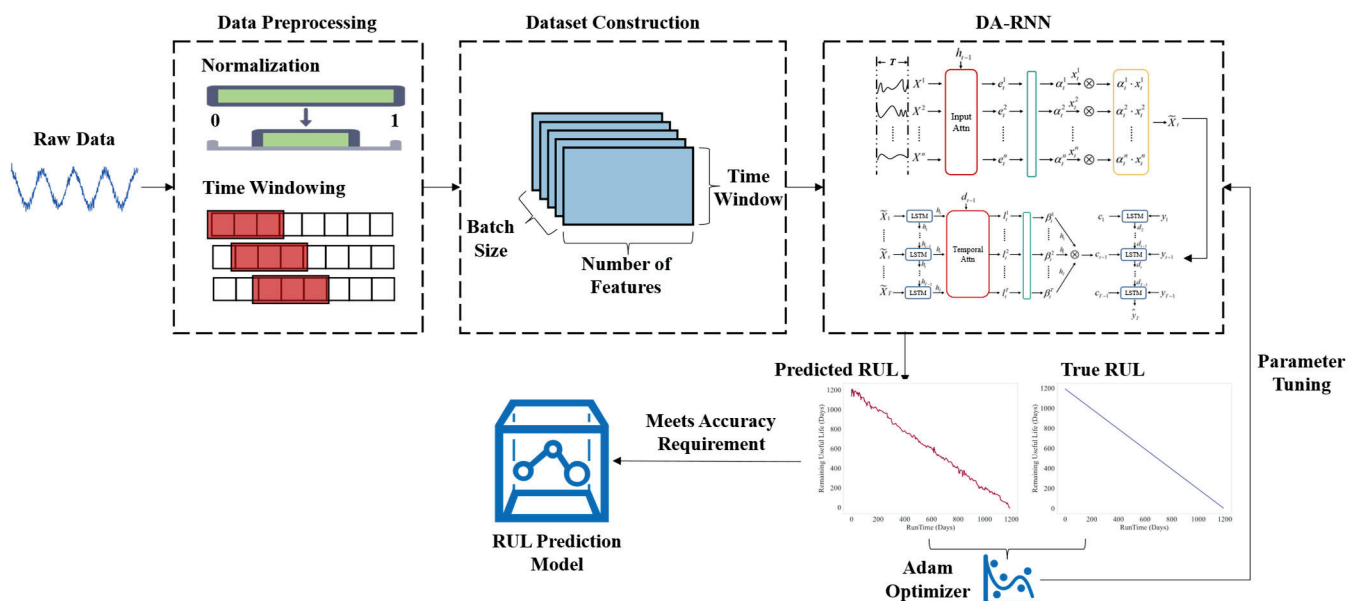


Figure 3. Schematic overview of the DA-RNN-based RUL prediction framework. The figure illustrates the overall network architecture and information flow from windowed multivariate inputs to RUL outputs, including the encoder–decoder structure and the placement of the attention modules.

The processed data are then fed into the DA-RNN architecture. In the encoder, the input-attention mechanism emphasizes feature dimensions most relevant to degradation evolution, while the LSTM captures nonlinear temporal dependencies in the monitoring signals. Attention weights are learned independently for each well based on its own input time series, allowing the model to adapt to different operating conditions rather than relying on averaged patterns across wells. Compared with conventional LSTM networks, this dual-stage attention structure improves the representation of complex industrial monitoring data. In contrast to Transformer-based architectures that typically require large datasets and higher computational cost, DA-RNN exhibits more stable training behavior with lower parameter complexity, making it suitable for field applications with limited sampling frequency and gradually evolving degradation. In the decoder, the temporal-attention mechanism selects historical time steps most relevant to the current prediction, enabling the model to focus on representative stages of the degradation trajectory and improve prediction accuracy. A single DA-RNN model is trained using data from multiple wells, with model parameters shared across wells, while each well is treated as an independent input sequence during training and inference.

The model is trained using the Adam optimization algorithm, which updates parameters based on the error between predicted and actual RUL values. Early stopping is employed to prevent overfitting, and validation loss is monitored to ensure convergence stability. Gradient clipping is applied when necessary to avoid numerical issues such as exploding gradients. A systematic exploration of key hyperparameters—including window length, learning rate, and hidden-layer size—is conducted to balance convergence speed, generalization capability, and computational cost. The dual-stage attention structure further strengthens the model’s ability to capture salient degradation-related information, resulting in more robust and reliable predictions in field scenarios. Once the model satisfies the predefined accuracy requirements during training, the construction of the RUL predic-

tion model is completed. The final model effectively characterizes the future degradation pattern of ESP systems and provides reliable support for maintenance planning, pump retrieval scheduling, and early-warning strategies in oilfield operations.

With the DA-RNN model established and validated for extracting degradation-sensitive temporal features and generating reliable RUL predictions, it becomes possible to further integrate the predictive model into production decision-making. To achieve this, an optimization framework is developed to determine the ESP operating regime that maximizes equipment lifespan based on the predicted RUL.

3.3. Optimization of ESP Operating Regime Based on RUL Prediction

To further utilize the RUL prediction model for practical production decision-making, an optimization framework is developed to determine the ESP operating regime that maximizes the equipment's remaining lifespan. Unlike model training, the objective here is to exploit the RUL predictions produced by the DA-RNN network to identify controllable operating parameters—such as pump frequency and surface choke setting—that yield the longest remaining life while meeting production and safety requirements. Production rates and pressure distribution are treated as response variables determined by a physics-based wellbore hydraulic model, while motor current, temperature, and efficiency are obtained from an empirical motor response model calibrated using historical operating data.

For each candidate operating regime V , representing a specific combination of controllable settings, the operating regime is defined as a decision vector:

$$V = [f, d] \quad (20)$$

where f denotes the ESP operating frequency and d represents the surface choke opening. Given a candidate regime V , the DA-RNN model outputs a RUL trajectory over a finite prediction horizon:

$$L(V) = \{L_k(V)\}_{k=1}^K \quad (21)$$

where $L_k(V)$ denotes the predicted remaining life at time step t_k and K is the total number of prediction steps within the evaluation horizon. In this study, the prediction horizon K was set to 100 days, corresponding to a typical operational planning cycle in the studied offshore field. This horizon also represents a range over which the DA-RNN model maintains strong predictive accuracy, as evidenced by the consistently low MAE observed within this time window, thereby balancing short-term operational responsiveness and robustness against long-term prediction uncertainty. Let V^0 denote the current operating regime and $\{L_k(V^0)\}$ the corresponding baseline lifespan trajectory.

The improvement introduced by a candidate operating regime V is quantified by the cumulative difference between the predicted lifespan trajectories before and after optimization, formulated as:

$$J(V) = \sum_{k=1}^K [L_k(V) - L_k(V^0)] \Delta t_k \quad (22)$$

where Δt_k denotes the time interval associated with the k -th prediction step and is consistent with the sampling interval used in the sliding-window construction. A positive and larger value of $J(V)$ indicates a more pronounced extension of the ESP lifespan relative to the baseline operating condition.

The optimization problem for determining the optimal ESP operating regime is thus formulated as:

$$\begin{cases} \max_{V \in \Omega} J(V) \\ q_o(V) \geq q_{o,\min} \text{ (minimum oil rate)} \\ q_l(V) \geq q_{l,\min} \text{ (minimum liquid rate)} \\ p_{wf}(V) \geq p_{wf,\min} \text{ (avoid liquid loading)} \\ I(V) \leq I_{\max} \text{ (motor current limit)} \\ T_m(V) \leq T_{m,\max} \text{ (motor temperature limit)} \\ \eta(V) \geq \eta_{\min} \text{ (pump efficiency constraint)} \\ V_{\min} \leq V \leq V_{\max} \text{ (engineering bounds)} \end{cases} \quad (23)$$

In the above formulation, $q_o(V)$ and $q_l(V)$ denote the oil and total liquid production rates, respectively; $p_{wf}(V)$ is the flowing bottom-hole pressure; $I(V)$ and $T_m(V)$ represent the motor current and motor temperature; and $\eta(V)$ denotes the pump efficiency under operating regime V .

In practice, the optimization is implemented using a discrete search strategy. The ESP operating frequency f and choke size d are discretized within prescribed engineering ranges $[f_{\min}, f_{\max}]$ and $[d_{\min}, d_{\max}]$, with increments Δf and Δd , respectively. In practical implementation, the frequency increment Δf is set to 1 Hz, while the choke size increment Δd follows discrete choke specifications expressed in mm/64th that are commonly used in field operations. Under these settings, the feasible search space Ω_{feas} for a typical well contains approximately 180–250 candidate operating regimes; evaluating the objective function for all candidates requires on the order of 2 min per well on a standard engineering workstation, which is sufficiently efficient for routine batch operational planning. For each candidate pair (f_m, d_n) , wellbore hydraulic calculations and motor electrical models are employed to determine the associated pressure distribution, temperature distribution, flow rate, and motor current, thereby forming the complete operating regime $V(f_m, d_n)$ and its corresponding response quantities $q_o(V)$, $q_l(V)$, $p_{wf}(V)$, $I(V)$, $T_m(V)$, and $\eta(V)$. The objective value $J(V(f_m, d_n))$ is evaluated for all feasible combinations. The optimal operating regime is obtained as:

$$V^* = \arg \max_{(f_m, d_n) \in \Omega_{\text{feas}}} J(V(f_m, d_n)) \quad (24)$$

where Ω_{feas} denotes the set of candidate frequency–choke combinations that satisfy all engineering and operational constraints in Equation (23). These constraints are defined based on equipment design limits, field operational guidelines, and historical operating envelopes derived from long-term offshore production data, ensuring that all candidate regimes remain physically feasible and operationally safe. For each individual well, the historical operating envelope is constructed by removing short-duration abnormal and extreme operating conditions and retaining the stable operating range observed during normal production, where operating frequency and choke size are limited to within $\pm 10\%$ of their long-term average values. This ensures that optimization is constrained within practically verified and stable field operating conditions. While the general form of the constraints is consistent across wells, the specific bounds of Ω_{feas} are allowed to vary from well to well to account for differences in reservoir inflow capacity, completion design, and equipment configuration. In addition, all optimized operating regimes are constructed within historical operating envelopes observed in field practice, and the recommended frequency and choke settings have been previously realized during normal operations. This ensures that the proposed optimization results are operationally feasible and do not rely on hypothetical or unrealizable control actions. The corresponding optimal regime

V^* yields the recommended ESP operating parameters, including pump frequency and choke size, along with the associated pressure, temperature, and flow-rate distributions.

This optimization strategy enables the DA-RNN-based RUL prediction model to be directly integrated into ESP operational planning, allowing operating parameters to be adjusted in a condition-aware manner. By guiding operational decisions using predictive degradation trends rather than fixed rules, the proposed framework maximizes equipment lifespan while maintaining safe and efficient production. In this study, the optimization is intended for batch operational planning rather than real-time control and is executed over predefined planning horizons using periodically updated operating data, which is consistent with practical offshore operating workflows. The effectiveness of the overall workflow, including feature selection, RUL prediction, and operating-regime optimization, is evaluated in the following Materials and Methods section using field data.

4. Materials and Methods

4.1. Model Pre-Training and Performance Evaluation

During the training phase, the Adam optimizer was employed to update the parameters of the DA-RNN model. The dataset contains nine selected features, with a batch size of 128 and a window length of 10. Both the encoder and decoder were configured with 64 hidden units, and the learning rate was set to 0.001. The model was trained for 100 epochs, and the mean squared error was used as the loss function. The dataset was divided into training, validation, and testing sets using a chronological split to preserve the temporal structure of the sequences. Model training was performed using only earlier operational data, while validation and testing were conducted on subsequent unseen periods. All preprocessing steps were performed exclusively on the training data and then consistently applied to the validation and testing sets, thereby avoiding data leakage and ensuring realistic prognostic evaluation. To reduce the effect of random initialization, each experiment was repeated five times, and the average performance was reported. Gradient clipping was also applied to avoid numerical instability during backpropagation. All model training was conducted on a workstation equipped with an NVIDIA RTX 50-series GPU (24 GB memory), an Intel Core i9 CPU, and 64 GB RAM. Under this hardware configuration, the total training time for the DA-RNN model was on the order of several hours, depending on the hyperparameter settings.

The training and validation errors of the DA-RNN model are shown in Figure 4, where the horizontal axis represents the number of training epochs and the vertical axis denotes the root-mean-squared error (RMSE). Since the training data were normalized in advance, the RMSE is dimensionless. As illustrated in Figure 4, both training and validation errors converge rapidly to a low level, demonstrating the stable learning and good fitting capability of the DA-RNN model.

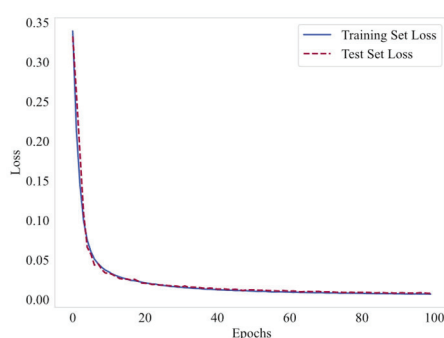


Figure 4. Training and validation loss curves of the DA-RNN model. The rapid convergence and stable behavior indicate effective learning of degradation patterns without overfitting.

The prediction performance of the DA-RNN model on the full dataset is shown in Figure 5, where the horizontal axis represents the true RUL (in days) and the vertical axis denotes the predicted RUL. The samples from both the training and testing sets lie close to the diagonal reference line $y = x$, indicating strong consistency between predicted values and actual observations. This demonstrates that the DA-RNN model achieves high prediction accuracy across a wide range of RUL values.

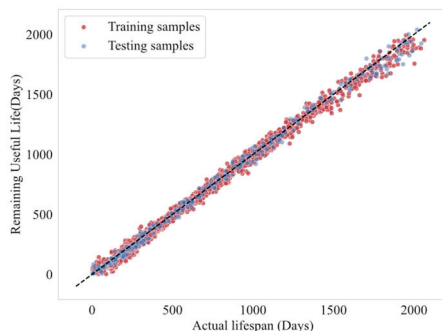


Figure 5. Comparison between predicted and true RUL values across the full dataset. The close alignment with the diagonal demonstrates high prediction accuracy over a wide range of lifespan stages.

To further validate the advantages of DA-RNN in time-series prediction tasks, additional RUL prediction models were constructed using RNN, LSTM, GRU, and Transformer architectures for comparison. All baseline models were trained under the same hyperparameter settings, including learning rate, batch size, window length, and number of epochs, to ensure a fair and unbiased comparison. For the Transformer baseline, a time series-oriented configuration was adopted rather than a generic sequence-modeling setup. An encoder-only architecture with positional encoding was used to preserve temporal order, and self-attention was applied on fixed-length sliding windows consistent with the RUL prediction task. Key architectural parameters were adjusted through preliminary testing to ensure stable convergence and reasonable performance under long-horizon degradation conditions. This design ensured that the Transformer baseline was appropriately tuned for time-series prognostics and fairly evaluated in the comparison.

The performance of each model was evaluated using three widely adopted metrics: mean relative error (MRE), mean absolute error (MAE), and root mean squared error (RMSE). The calculation formulas for these metrics are given in Equations (25)–(27).

$$\text{MRE} = \sum_{i=1}^n \left| \frac{y_t - y_{\text{pre}}}{y_t} \right| \times \frac{1}{n} \quad (25)$$

$$\text{MAE} = \frac{\sum_{i=1}^n |y_t - y_{\text{pre}}|}{n} \quad (26)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_t - y_{\text{pre}})^2} \quad (27)$$

In these equations, y_t denotes the true RUL, $y_{t,\text{pre}}$ denotes the predicted RUL, and n is the sample size. MRE measures the relative deviation between predicted and true values and reflects the model's ability to remain accurate across different scales of RUL. MAE reflects the average absolute difference between predicted and actual values. RMSE introduces a squared penalty and is therefore more sensitive to large deviations; a lower RMSE indicates that even the worst prediction errors remain well controlled. All metrics are computed on a per-well basis, and the reported values are obtained by averaging the errors across all wells.

The comparative evaluation results are presented in Figure 6. It is evident that the DA-RNN model consistently achieves lower MRE, MAE, and RMSE than the RNN, LSTM, GRU, and Transformer models. This indicates superior predictive performance under both typical and extreme conditions. In relative terms, the proposed DA-RNN achieves a substantial reduction in prediction error. On the test set, the MAE is reduced by approximately 78% compared with the best-performing baseline model (LSTM), while consistently outperforming all other evaluated architectures. Figure 6 also includes two single-attention variants for ablation analysis, namely InputAttOnly and TempAttOnly. The results show that removing either the input attention mechanism or the temporal attention mechanism leads to a clear increase in prediction errors on both training and test sets. Compared with these single-attention variants, the full DA-RNN achieves an additional MAE reduction of approximately 73–75%, demonstrating that the two attention components play complementary roles in enhancing RUL prediction accuracy. The results confirm that the dual-stage attention mechanism of DA-RNN enables it to better extract degradation patterns embedded in multivariate ESP operating data, thus delivering more accurate and reliable RUL predictions. The performance gain can be attributed to the ability of DA-RNN to selectively emphasize degradation-relevant features and to capture key temporal patterns that are critical for accurate RUL estimation. From an operational perspective, prediction errors should be interpreted in relation to the time scale of ESP operation. Since operating adjustments and maintenance planning are typically conducted over horizons of tens to hundreds of days, the MAE reduction achieved by the proposed DA-RNN represents a meaningful improvement in the timing accuracy of operational decisions rather than a purely numerical gain.

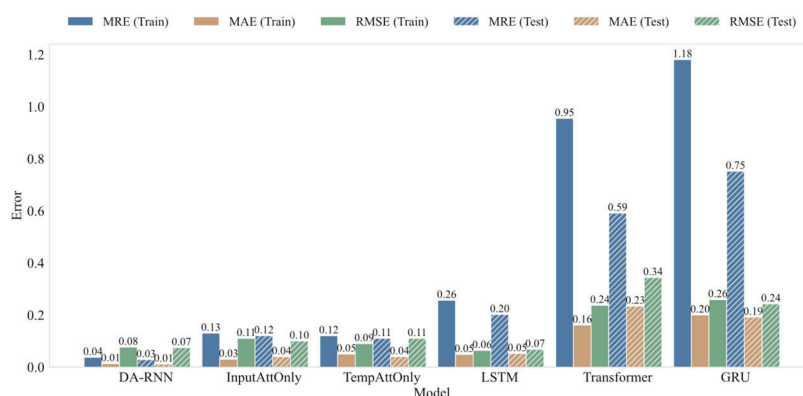


Figure 6. Performance comparison of DA-RNN with baseline models. DA-RNN consistently achieves lower prediction errors, highlighting the benefit of dual-stage attention in capturing degradation patterns.

To ensure the stability and robustness of the DA-RNN model, a comprehensive hyperparameter optimization procedure was conducted. A k-fold cross-validation strategy was adopted, in which the dataset was divided into k subsets, with k minus one subsets used for training and the remaining subset used for validation. This process was repeated k times so that each subset served once as the validation set. The average validation performance over k iterations was taken as the evaluation metric for each hyperparameter configuration. Considering the relatively large size of the dataset used in this study and the computational cost associated with cross-validation, the value of k was set to 5.

A grid search was then performed to examine the effect of key hyperparameters on the prediction performance of the DA-RNN model. The hyperparameters included the window length, learning rate, and the number of hidden units in the encoder and decoder. Prior to the grid search, the candidate range of window length (5–20) was determined

based on the data resolution and practical ESP operating characteristics. The lower bound ensures sufficient recent context to capture short-term fluctuations and early degradation cues, while the upper bound avoids overly long windows that may dilute recent condition changes and increase computational cost. Specifically, the window length was varied from 5 to 20 with a step of 5, the learning rate ranged from 0.001 to 0.1 with a step of 0.001, and the number of hidden units in both the encoder and decoder ranged from 64 to 256 with a step of 64, resulting in a total of 6400 evaluated combinations. The grid search results are summarized in Table 2. As shown in the table, a window length of 20 and a learning rate of 0.001 yielded the lowest prediction errors, while using 64 hidden units in both the encoder and decoder provided the most stable performance. Based on these results, the final model configuration consistently adopts the optimal hyperparameter combination identified by the grid search, including a window length of 20, a learning rate of 0.001, and 64 hidden units in both the encoder and decoder. Grid search was chosen because the hyperparameter space is low-dimensional and well bounded, allowing for exhaustive evaluation without prohibitive computational costs.

Table 2. Performance comparison of different parameters of the DA-RNN model.

Window Length	Learning Rate	Number of Encoder Hidden Units	Number of Decoder Hidden Units	MRE	MAE	RMSE
20	0.001	64	64	0.0208	0.0043	0.0055
20	0.001	128	128	0.0254	0.0069	0.0091
10	0.001	64	64	0.0287	0.0072	0.0098
10	0.003	128	128	0.0561	0.0100	0.0108
15	0.002	64	64	0.0273	0.0082	0.0109
15	0.001	64	64	0.0369	0.0096	0.0112

These findings suggest that a relatively long input window enables the DA-RNN model to capture richer temporal degradation information from the ESP operating data. A lower learning rate enhances training stability and reduces the risk of undesirable oscillation during optimization. Increasing the number of hidden units slightly improves representation capability, but excessively large hidden layers do not yield additional benefit. Overly complex configurations may even cause overfitting, which degrades prediction accuracy on the testing set. Based on these observations, the final hyperparameter settings of the DA-RNN model were selected as follows: window length of 20, learning rate of 0.001, 64 hidden units in the encoder, and 64 hidden units in the decoder.

In addition to the grid search, several supplementary analyses were conducted to further verify the reliability of the selected hyperparameters. First, each candidate configuration was trained multiple times using different random seeds. This ensured that the superior performance of the chosen configuration was not the result of a single initialization. Second, the learning curves corresponding to each configuration were examined to verify convergence stability. Hyperparameter combinations that exhibited irregular fluctuations in the validation error or failed to converge were excluded. Third, the sensitivity of the model to variations in window length, learning rate, and hidden units was analyzed. The final configuration demonstrated high robustness, as moderate perturbations to these hyperparameters did not lead to significant performance degradation.

These analyses confirm that the selected hyperparameter configuration provides a stable balance between model complexity and predictive accuracy. In addition, the variability across repeated experiments was examined to assess the robustness of the model performance. All reported results in this section were obtained by repeating the training process multiple times with different random initializations. The observed variation in prediction errors across runs remained limited, indicating stable convergence behavior and

low sensitivity of the DA-RNN model to random initialization. The chosen settings form a reliable foundation for subsequent RUL prediction and the optimization of ESP operating regimes presented in the following sections.

4.2. Analysis of RUL Prediction Behavior Under Actual ESP Operating Conditions

To assess the practical applicability of the proposed RUL prediction framework, the model was applied to representative ESP operating data. The prediction results are presented in Figure 7, where the horizontal axis denotes the actual operating time of the ESP and the vertical axis represents the RUL in days. The predicted RUL curve closely matches the true degradation trajectory across the entire operating period. This indicates that the DA-RNN model can reliably capture both long-term degradation patterns and short-term dynamic variations present in real ESP operation. For the representative well shown in Figure 7, the MAE between the predicted and actual RUL is 23 days, quantitatively confirming the high prediction accuracy suggested by the visual agreement of the curves.

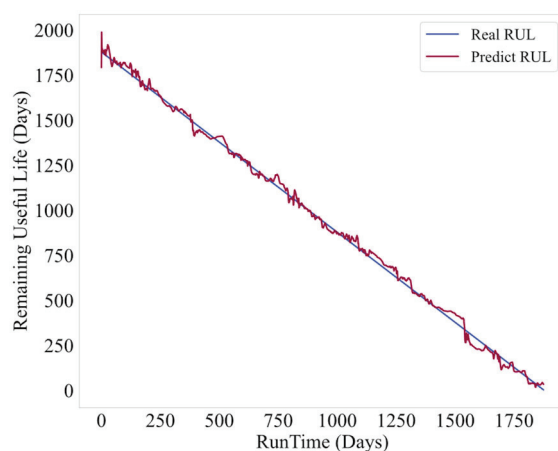


Figure 7. RUL prediction results for a representative ESP well. The predicted trajectory closely follows the actual degradation trend, demonstrating the model’s capability to capture both long-term decline and short-term fluctuations.

In addition to the overall agreement between predicted and true RUL values, the behavior of the model under different operating conditions provides further insights. Figure 8 illustrates RUL prediction results for ESPs with relatively short operational lifespans. For ESPs operating for fewer than 1000 days, the RUL decreases rapidly during early production. For these short-lifespan ESP wells, the MAE of the RUL predictions in Figure 8a–d is 57, 54, 68, and 70 days, respectively. Production data show that these wells typically exhibit limited inflow capacity at the beginning of operation. For example, the well corresponding to Figure 8a experienced low liquid production during the first 50 days and operated at an average pump frequency of approximately 55 Hz. In contrast, wells with higher lifespans, such as the example shown in Figure 8b, maintained more stable inflow conditions during early operation. The ESP in Figure 8b operated at an average frequency of 48 Hz in the first 200 days, and its RUL curve exhibited much smaller fluctuations, with a maximum deviation of only 14.6 percent. These observations demonstrate that early-stage inflow stability plays an essential role in shaping the degradation behavior of ESP systems.

Further interpretation of the degradation process is shown in Figure 8c. In this case, the predicted RUL exhibits a marked decline during the mid-life stage. According to field monitoring data, the pump intake temperature exceeded 120 degrees Celsius during this period. The elevated temperature accelerated insulation ageing and increased the risk of gas lock. As inflow gradually weakened, the ESP was operated at high frequency for extended periods in an effort to maintain production. Prolonged high-frequency oper-

ation led to increased motor current and additional internal heating, which intensified electrical and mechanical degradation mechanisms. These factors collectively reduced pump efficiency and shortened the RUL of the ESP. The DA-RNN model successfully captured this accelerated degradation stage, as reflected by the steep drop in the predicted RUL curve. This demonstrates that the model responds sensitively to variations in operational parameters such as motor temperature, motor current, and intake pressure. This behavior further illustrates that the dual-stage attention mechanism enables the model to focus on combinations of feature patterns—such as concurrent temperature elevation and current surges—that typically precede accelerated deterioration, thereby generating RUL trajectories that closely reflect underlying physical responses.

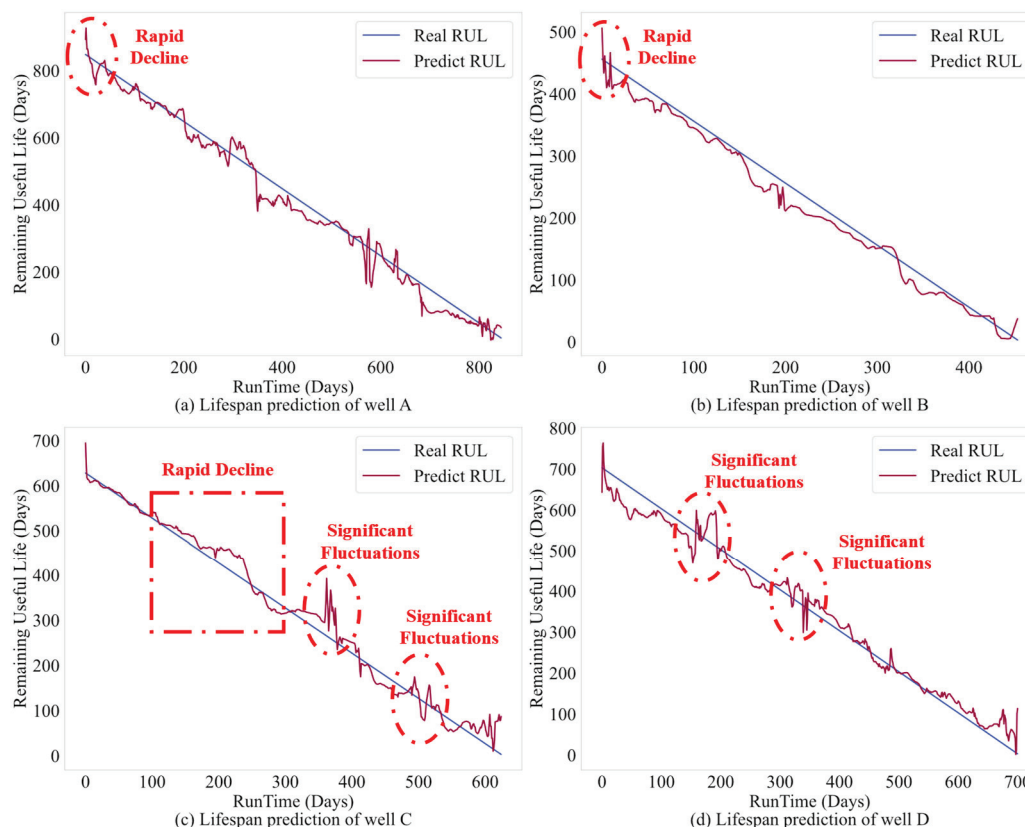


Figure 8. RUL prediction results for ESP wells with relatively short lifespans: (a) predicted and observed RUL trajectories for low-lifespan well-A; (b) predicted and observed RUL trajectories for low-lifespan well-B; (c) predicted and observed RUL trajectories for low-lifespan well-C; and (d) predicted and observed RUL trajectories for low-lifespan well-D. The four subfigures present representative cases of ESP wells operating in late-life stages, illustrating how different operating conditions are reflected in the predicted RUL trajectories.

A similar degradation pattern is observed in Figure 8d, where the RUL curve exhibits pronounced oscillations throughout the mid-to-late production period. Field data indicate that these fluctuations coincide with repeated cycles of inflow instability, during which the ESP experienced alternating periods of liquid fallback and transient gas interference. These conditions caused the motor current to rise sharply and intermittently, reflecting abrupt changes in hydraulic load. The frequent transitions between liquid-rich and gas-invaded flow not only increased the risk of partial gas lock but also forced the pump to operate away from its best-efficiency region. As a result, both electrical and mechanical stresses accumulated more rapidly, contributing to the accelerated decline in RUL observed in the prediction. The DA-RNN model captured these oscillatory degradation patterns effec-

tively, demonstrating its capability to track fine-scale dynamic disturbances in operating parameters and to translate them into corresponding changes in the RUL trajectory.

Overall, the analysis confirms that the DA-RNN model can accurately reflect diverse degradation behavior under field operating conditions. The model captures both macro trends and micro dynamic responses in the degradation process, enabling early identification of adverse operating states and supporting timely intervention in ESP management. These findings highlight the model's practical value for deployment in real production environments.

4.3. Analysis of Operating Strategy Optimization for ESP Systems

To further evaluate the practical value of the proposed RUL prediction framework, this section investigates how RUL-informed insights can guide the optimization of ESP operating strategies. Two representative wells, denoted as well-E and well-F, were selected to illustrate the impact of optimization on the predicted RUL trajectory under actual field conditions. Figures 9 and 10 compare the predicted RUL under the historical operating regime with the predicted RUL under an optimized operating regime derived from RUL-based recommendations.

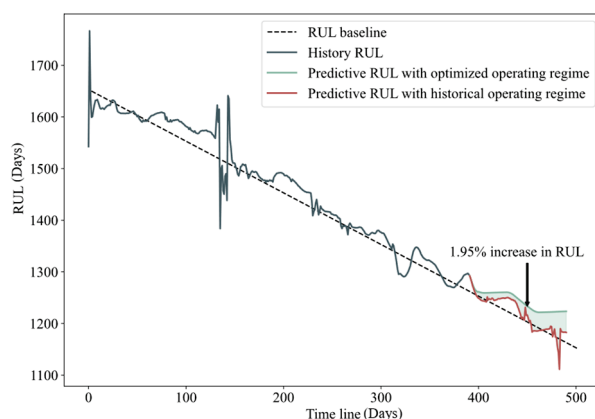


Figure 9. Comparison of predicted RUL under historical and optimized operating regimes for well-E. The optimized strategy stabilizes the degradation trajectory and mitigates abrupt RUL drops.

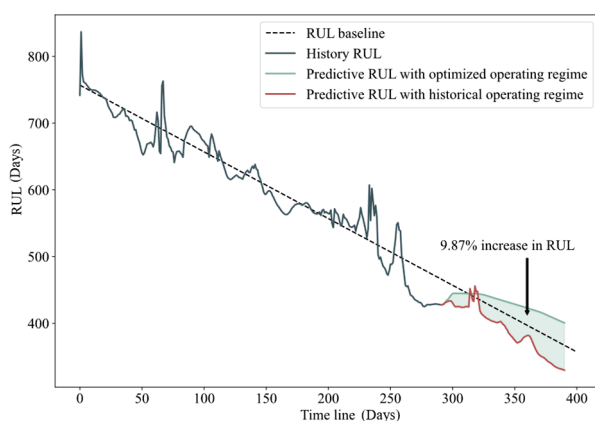


Figure 10. Comparison of predicted RUL under historical and optimized operating regimes for well-F. The optimized regime substantially slows degradation progression in wells with volatile operating conditions.

For well-E, the historical operation shows a steady decline in RUL, with occasional sharp drops corresponding to periods of elevated current draw and increased thermal stress. These abrupt declines are typically associated with transient increases in motor

loading caused by inflow fluctuations or liquid-column oscillations. When the optimized operating strategy is applied, the predicted RUL curve becomes noticeably smoother toward the end of the operating timeline. Although the overall improvement is modest, with an increase of approximately 1.95% in predicted RUL, the optimized operating regime extends the RUL by approximately 18 days at the end of the 100-day optimization period, effectively suppressing the severe downward excursions observed under historical operation. The optimization primarily aligns pump frequency with real-time inflow capacity, reduces unnecessary high-frequency operation near the pump's optimal efficiency region, and mitigates abrupt load transitions, thereby alleviating cumulative electrical and thermal stress.

For well-F, the effect of optimization is more pronounced. Under historical operation, the RUL exhibits a rapid decline after approximately 320 days, coinciding with frequent inflow instability and repeated frequency adjustments. These operational patterns drive the pump to traverse its best-efficiency region multiple times, amplifying cyclic loading and accelerating electrical and mechanical degradation. When the RUL-guided optimization strategy is applied, the degradation rate is significantly reduced, resulting in a 9.87% increase in predicted RUL. Over the optimization horizon, this improvement corresponds to an absolute extension of approximately 45 days in RUL, and the optimized RUL trajectory remains substantially flatter, indicating that stabilizing operating conditions and avoiding sustained high-stress states can effectively slow degradation progression in wells subject to volatile operating environments.

To extend the single-well analysis to the platform scale, a comparative evaluation was conducted using wells with similar background conditions, including comparable pump–motor capacity levels, commissioning age, pump-setting depth, well inclination, and operating envelopes. Based on whether the RUL-guided optimization strategy was applied, the selected wells were classified into Group A (RUL-guided operation) and Group B (experience-based operation). A concise platform-level comparison of the two groups is summarized in Table 3.

Table 3. Platform-level comparison of ESP wells with and without RUL-guided optimization.

Category	Metric	Group A: RUL-Guided Operation	Group B: Experience-Based Operation
Well characteristics	Number of wells	18	21
	ESP configuration	ESP wells with comparable pump–motor capacity levels	ESP wells with comparable pump–motor capacity levels
	Average commissioning age (years)	4.6	4.9
	Average pump-setting depth, PSD (m)	2350	2380
	Average well inclination (°)	21.4	22.7
Operating conditions	Average water cut (%)	61.3	63.1
	Average liquid rate (m ³ /d)	432	445
Reliability indicators	Annualized shutdown rate (events per well-year)	0.42	0.53
	Non-planned shutdown events (events per well-year)	0.31	0.39

Table 3 shows that, under comparable geometric and operating conditions, wells operated with RUL-guided optimization exhibit lower annualized shutdown rates and fewer non-planned shutdown events than those operated under conventional strategies. All operating regimes considered are constrained by existing engineering limits and fall within historically observed field ranges, indicating that the comparison reflects feasible operational behavior rather than purely hypothetical control scenarios.

To further interpret these platform-level differences, aggregated operational behaviors of the two groups were examined. Wells operated under experience-based strategies tend to exhibit frequent short-term adjustments in operating frequency and current in response to inflow fluctuations, increasing exposure to transient high-load and high-stress conditions. In contrast, wells operated with RUL-guided optimization generally maintain more stable operating regimes, with fewer abrupt load transitions and reduced residence time in sustained high-stress states. This systematic difference in operational behavior provides a practical explanation for the lower shutdown-related event frequency observed at the platform scale and links the statistical trends in Table 3 to physically interpretable operating patterns.

This stability is also reflected in the response of the optimization results to small perturbations in key input variables. When inflow-related parameters, pressure conditions, and electrical load indicators vary within a narrow range representative of normal measurement uncertainty, the resulting changes in the optimization objective remain below approximately 2 percent and the recommended frequency–choke combinations do not exhibit material variation across the discretized operating space. This observation indicates that the RUL-guided optimization produces robust and stable operating recommendations rather than highly sensitive control decisions.

Beyond robustness, the reliability indicators in Table 3 also imply the tangible operational and economic benefits of the RUL-guided optimization. Compared with experience-based operation, Group A shows a lower non-planned shutdown frequency (0.31 vs. 0.39 events per well year), i.e., 0.08 fewer unplanned events per well year, which corresponds to approximately 1.68 fewer events per year across the 21 wells in Group B. Under the reported operating conditions, the average oil rate is in the order of 164–167 m³/d. Assuming a typical offshore downtime of $D = 1\text{--}5$ days per non-planned shutdown, an oil price of 75 USD/bbl (≈ 472 USD/m³), and a direct corrective-intervention cost of 30–80 k USD per event, the reduced shutdown frequency implies about 13–67 m³ of protected oil production per well per year ($\approx 6\text{--}32$ k USD/yr in avoided production loss) and an additional $\approx 2\text{--}6$ k USD/yr in reduced intervention costs, yielding combined savings of roughly 9–38 k USD per well per year; at the 21-well scale, this corresponds to $\approx 0.18\text{--}0.79$ M USD per year. These estimates, while scenario-dependent, quantitatively link the reliability improvements to reduced downtime risk and a lower corrective-maintenance burden under engineering-feasible operating regimes.

In addition, the interaction between prediction-based optimization and subsequent operation is discussed as follows. Because optimized operating adjustments may influence subsequent system behavior, overly frequent interactions between RUL prediction and operating adjustment could increase operating fluctuations. In this study, the DA-RNN model was trained offline and applied without online updating; operating adjustments were implemented in a controlled manner. This design helps to maintain stable and realistic operating regimes consistent with field practice.

Overall, the comparative analysis demonstrates that the effectiveness of RUL-guided optimization depends on baseline operating stability. Wells with relatively stable inflow conditions tend to show incremental improvements, whereas wells subjected to volatile or rapidly deteriorating conditions can experience substantial extension in predicted RUL. Across both single-well cases and platform-level evaluation, the results consistently indicate that RUL-informed operational adjustment not only delays degradation but also stabilizes system behavior. These findings confirm that the proposed framework can translate degradation predictions into actionable operational guidance, supporting proactive, data-driven optimization of ESP performance. Importantly, the observed reduction in shutdown risk is

associated with engineering-constrained and historically consistent operating adjustments, rather than representing a purely model-level counterfactual outcome.

5. Conclusions

This study proposed an RUL prediction framework for ESP systems based on a DA-RNN architecture. By integrating input attention and temporal attention mechanisms, the model effectively identifies key degradation-related variables and captures long-term dependencies in multivariate time series. Validation using data from 712 ESP wells demonstrated that the proposed method provides superior prediction accuracy compared with conventional RNN, LSTM, GRU, and Transformer models.

Through detailed analysis of field operating data, the model was shown to reliably reproduce both long-term degradation trends and short-term dynamic responses. The case studies demonstrated that the RUL framework can reveal degradation precursors associated with high-frequency operation, thermal stress, current fluctuations, and inflow instability. Furthermore, by linking RUL evolution with controllable operating parameters, the framework provides actionable insights for optimizing ESP operation. The optimization results from representative wells showed that RUL-informed adjustments help to stabilize degradation trajectories and extend equipment lifetime, with improvements ranging from incremental gains to substantial lifespan extension, depending on well conditions.

Although the present framework focuses on point-wise RUL estimation and does not explicitly incorporate uncertainty quantification, the proposed optimization strategy relies primarily on the relative variation and temporal trends of predicted RUL rather than absolute point values. In addition, failure definitions and failure-time labeling are based on field records and maintenance logs, which may involve ambiguity due to early pull-outs or non-failure shutdowns. Moreover, the model was developed and validated using data from a specific offshore oilfield and ESP configuration; its generalization to other fields or operating conditions may require further validation. Nevertheless, the consistent RUL response trends under different operating regimes provide practical guidance for lifespan-oriented decision-making, supporting the applicability of the proposed framework for operation optimization in real field environments.

Overall, the results demonstrate that integrating RUL prediction into ESP management workflows delivers meaningful operational benefits. The DA-RNN-based approach enables the early identification of adverse operating states, supports proactive adjustment of production strategies, and provides a reliable data-driven foundation for enhancing equipment reliability. Given its low computational cost and reliance on routinely collected field parameters, the proposed framework can be readily integrated into existing ESP monitoring infrastructures to support real-time decision-making and life-extension management in ESP-driven oilfield production.

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Conflicts of Interest: Author Bin Liu was employed by the company Petro China Jidong Oilfield Company; Author Yangnan Shangguan was employed by the company Petro China Changqing Oilfield Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Article

Experimental Study on Mechanism of Using Complex Nanofluid Dispersions to Enhance Oil Recovery in Tight Offshore Reservoirs

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Abstract

Horizontal wells combined with multi-stage fracturing are key techniques for extracting tight oil formation. However, due to the ultra-low permeability and porosity of reservoirs, energy depletion occurs rapidly, necessitating external supplements to sustain production. During the hydraulic fracturing process, large volumes of fracturing fluid are injected into reservoirs, increasing its pressure to a certain extent. However, due to the oil-wet nature of the formation, the fracturing fluid cannot penetrate the rock, failing to enhance oil recovery during the shut-in period. Surfactant-based nanofluids have been introduced as fracturing fluid additives to reverse rock wettability, thereby boosting imbibition-driven recovery. Although the imbibition has been studied to inspire the tight oil recovery, few studies have demonstrated the imbibition in enhanced fossil hydrogen energy, which further promotes the imbibition recovery. In this paper, complex nanofluid dispersions (CND) have been proved to enhance the tight reservoir pressure. Through contact angle and imbibition experiments, it is shown that CND can transform oil-wet rock to water-wet, reduce the adhesion of oil, and improve the ultimate oil recovery through the imbibition effect. Then, core flow testing experiments were conducted to show CND can decrease the flow resistance and improve the swept area of the injected fluid. In the end, pressure transmission tests were conducted to show CND can enhance the formation energy and production after fracturing. Results demonstrate that CND enables the fracturing fluid to travel further away from the hydraulic fractures, thus decreasing the depletion of tight formation pressure and maintaining a higher oil production rate. Results help optimize the design of the hydraulic fracturing of tight offshore reservoirs.

Keywords: imbibition; wettability; surfactant; hydraulic fracturing; enhanced oil recovery; offshore reservoirs

1. Introduction

Unconventional reservoirs are acknowledged as vital contributors to global fossil energy supplies [1]. Tight offshore reservoirs also act as the vital part of petroleum and gas reservoirs. Despite their low permeability and porosity, their vast spatial extent results in substantial original oil in place (OOIP). Horizontal drilling and multi-stage hydraulic fracturing have become the primary techniques for oil extraction from these reservoirs. However, production rates tend to decline rapidly, yet ultimate recovery rates rarely exceed 5–10% of the OOIP [2,3]. Due to the low permeability of the reservoir, the reservoir pressure

in the distal area cannot propagate promptly after the bottomhole flowing pressure is reduced. Hence, numerous studies have been conducted to use gas to improve the reservoir pressure [4–8]. However, due to the high cost of gas resource (CO₂) and injection equipment, this technique remains challenging to enhance reservoir pressure in the grim situation of low oil prices.

During the hydraulic fracturing process, substantial quantities of fracturing fluid are injected into the reservoir formation under high pressure, causing the reservoir's internal pressure to increase by nearly one to two times. If the fracturing fluid rather stays in reservoirs than flows back to the surface, more reservoir pressure and production would be enhanced. The fracturing fluid would be more efficiently applied. Fracturing fluid that stays in reservoirs can help enhance reservoir pressure and production, which can be more efficiently applied. Imbibition is the primary mechanism enabling fracturing fluids to remain in reservoirs, making it a core technique for enhanced oil recovery (EOR) in tight formations [9]. Driven by capillary forces, aqueous fracturing fluids infiltrate pores and throats autonomously, displacing crude oil toward fractures [10,11], and finally, the fracturing fluid stays in the rock and enhances elastic energy. Wettability of the reservoir is the decisive factor for the whether imbibition happens or not [12,13]. The wettability of the reservoir rock determines the extent to which water penetrates the rock. After prolonged contact with crude oil, the reservoir often becomes oil-wet because the polar compounds in the oil adsorb onto the rock surface under the influence of reservoir pressure and temperature. In this case, imbibition of the fracturing fluid will not occur unless the reservoir rock is altered to a water-wet state. Once the reservoir rock becomes water-wet, the fracturing fluid can remain in the reservoir, helping to enhance the formation pressure and ultimately improve oil recovery [14–16].

Surfactants are commonly employed to modify reservoir wettability, with documented success in enhancing recovery from unconventional reservoirs [17–24]. Their mechanisms include two key aspects: first, lowering interfacial tension to reduce flow resistance and enhance production [25–27]; second, reversing oil-wet surface properties to water-wet conditions, which stimulates spontaneous imbibition [28–31]. In addition, surfactants also enhance the oil recovery through emulsification [32–35]. However, due to surfactants being easier to adsorb on the rock surface, the effective spread area of surfactants is limited [36–39]. In recent years, surfactants have been assembled into nanofluid to reduce the adsorption and enhance recovery. Reduced adsorption of liquid nanofluids on rock surfaces has been confirmed in prior studies [40,41]. Penny et al. demonstrated nanofluid could improve the production and net present value in shale reservoirs during hydraulic fracturing [42,43]. Liang et al. has proved that the nanofluid can reduce the adsorption, and also prove the nanofluid could alter the wettability [44]. Zhou et al. also demonstrated that the nanofluid could reduce the interfacial tension (IFT) and enhance production in the field [45]. Franco also proves the application of nanofluid during the cyclic steam stimulation process [46]. Other studies have used different kinds of nanofluids to prove the function [47–50].

The above studies have demonstrated that nanofluid could reduce the adsorption, alter the wettability, and improve relative permeability to oil. However, there are few studies devoted to the mechanism of nanofluids from the perspective of enhancing reservoir pressure. In this paper, several experiments have been conducted to try to answer this question. Contact angle and spontaneously imbibition test were conducted to testify wettability alteration and decrease adhesive force. To demonstrate that complex nanofluid dilutes (CND) could inspire the fracturing fluid traveling further into the formation, core flooding test was applied to demonstrate reducing the flow resistance after using CND. Most importantly, it was demonstrated that the CND could enhance the system pressure and enhance oil recovery based on the pressure transmission test (PTT). Clarifying this

issue can provide theoretical guidance for further expanding the widespread application of CND in oilfields, offer support for further enhancing CND performance, and additionally provide extra insights into revealing the mechanism by which CND boost oil production.

2. Material and Procedure

Rock properties: Rock specimens were collected from the Jimsar Formation in Xinjiang Oilfield, China, exhibiting a permeability of 1 μ D and porosity of 0.1. The average of pore throat is around 0.1 to 0.3 μ m. The mineral composition is detailed in Table 1, which is tested by XRD. The formation water salinity is 20,000 ppm; therefore, a 2 wt. % KCl solution was prepared to mimic formation water salinity. Additionally, the rock exhibits weak water sensitivity [51,52]. The rock wettability is of a mixed type, meaning that some pores and pore throats are oil-wet, while others are water-wet. Rock samples with a diameter of 2.54 cm and a length of approximately 2 cm were used for contact angle experiments, while samples with a length of about 5 cm were used for imbibition and fracturing fluid transfer experiments. Samples are the same except for the length. Rock A, B, C, D, and E are all from the Jimsar Formation; they are from the same formation.

Table 1. Mineral composition of rocks.

Non-Clay Mineral (%)				Clay Mineral (%)
Quartz	Plagioclase	Calcite	Ankerite	
10.34	26.88	5.17	55.82	1.79

CND: CND is a diluted nanostructure liquid. The core of CND is oil phase, which is a kind of alcohol. The surfactant adsorbs on the oil phase. The dispersed phase contains 10% alkanes or olefins as the oil cores. In total, 30–50% nonionic surfactant was used to stabilize the oil cores. A total of 20–40% alcohol was chosen as the co-solvent. Its mass concentration is usually 0.1–0.2 wt. %. In this study, 0.15 wt. % was added into the brine, which is composed of 2 wt. % KCl and distill water. The average diameter of CND is 15 nm, IFT of CND and kerosene is 3 mN/m, the IFT was tested by Du Noüy Ring method. Adsorption is 3 mg/g, and viscosity is 1.1 mpa.s at 25 °C. CND features a unique oil-in-water structure (alcohol-based oil core + nonionic surfactant + co-solvent) different from conventional inorganic nanoparticle-based nanofluids. It exhibits lower adsorption (3 mg/g), better wettability reversal effect (oil-wet $\rightarrow$ water-wet), and higher imbibition recovery compared to existing systems, highlighting its scientific uniqueness.

Amott cell: The cell (Figure 1) accommodates cylindrical core samples up to 6 cm in length, featuring a measurement accuracy of 0.02 mL within a 0–2 mL operational range. The apparatus is equipped with a top-mounted sealing cap to prevent liquid evaporation, while a centrally positioned capillary tube enables real-time monitoring of oil–water interface dynamics.

Contact angle equipment: The apparatus (Figure 2) was employed to determine the contact angle between solid surfaces and liquids. The measurement protocol consisted of depositing a 10 μ L droplet onto the rock surface, with subsequent image acquisition using a high-resolution digital camera. Following optimization of camera focus to achieve sharp droplet imaging, the liquid droplet profile on the rock substrate was displayed on the computer interface, enabling precise quantification of the solid–liquid contact angle through specialized image analysis software.

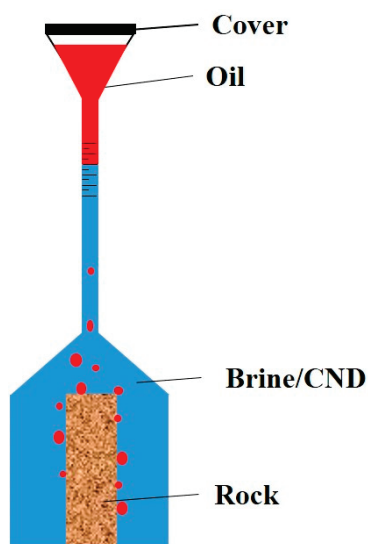


Figure 1. Schematic diagram of Amott cell.

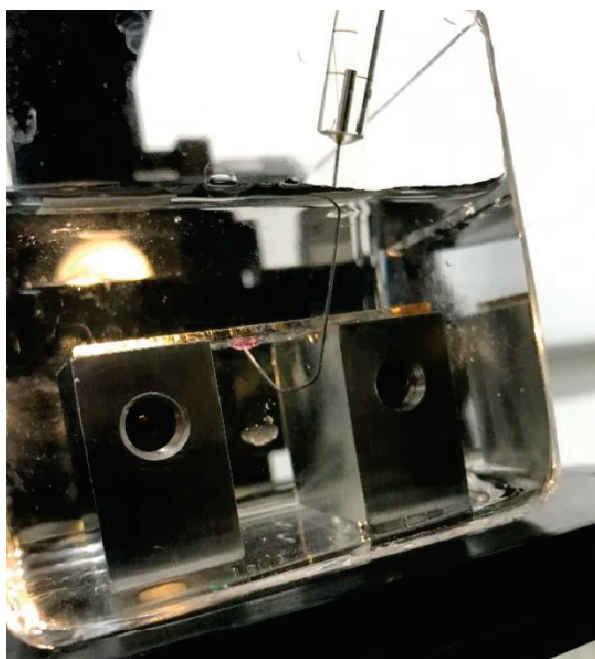


Figure 2. Contact angle test.

Core flow testing system: The core flow system (Figure 3) is composed of seven components. The power system utilizes a ISCO pump, which offers a flow rate ranging from 0.001 mL/min to 50 mL/min and can reach a maximum pressure of 70 MPa. There are three containers available, each designed to hold water, CND, and kerosene, respectively. These containers have a pressure-bearing capacity of 70 MPa. Five pressure sensors are installed to monitor pressure, with an accuracy of 0.4 kPa. Rock samples of varying lengths are loaded into the Hassler core holder, and the diameter of these rock samples is 2.54 cm. A manual pump is used to apply confining pressure, while a nitrogen cylinder provides backpressure. A signal adapter and a computer are employed to monitor pressure and weight signals.

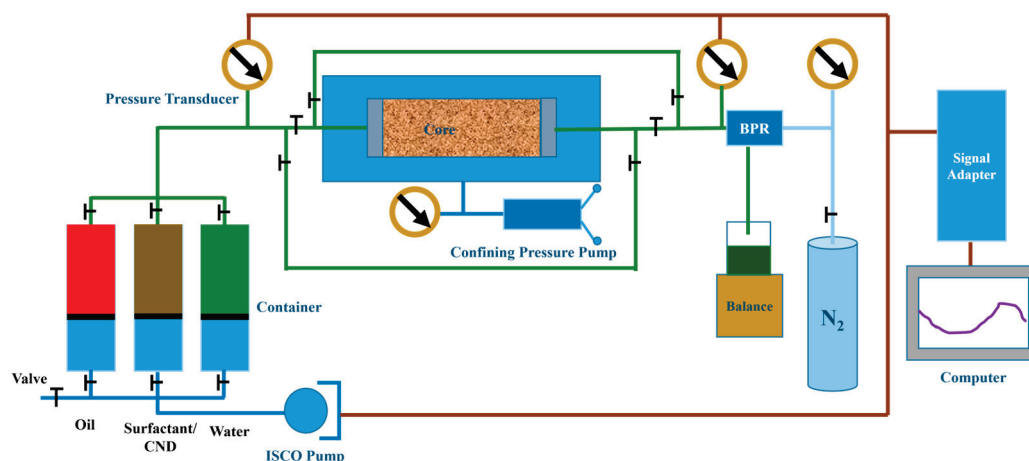


Figure 3. Schematic diagram of the core flow testing system.

Pressure transmission test (PTT): The Pressure Transmission Technique (PTT) setup (Figure 4) is utilized to measure degree of formation damage, capillary entry pressure, and the permeability in shale and tight oil reservoirs. In this research, the PTT is applied to investigate formation damage and enhanced pressure fracturing. The PTT includes a power system featuring a pump, 3 containers designed to hold water, CND, and kerosene, respectively, each with a pressure-bearing capacity of 35 MPa. Rock slices for PTT experiments are bonded using an epoxy resin–hardener mixture (1:1 mass ratio), then cut to a length of 0.7 cm and a diameter of 6.35 cm.

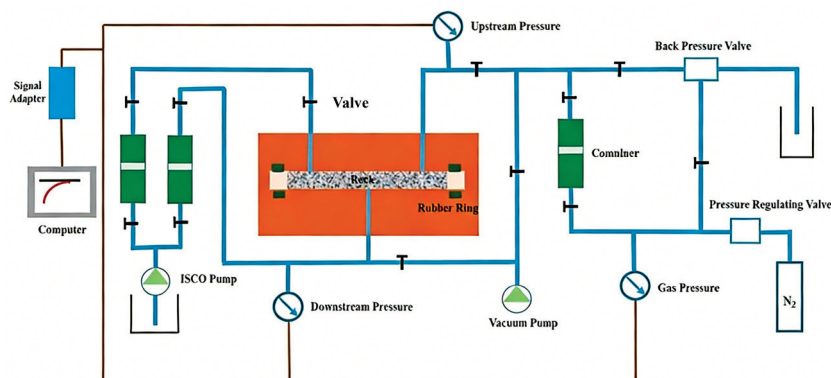


Figure 4. Schematic diagram of the PTT system.

Procedure:

Contact Angle Test:

Rock A samples were ground with 200–300 mesh sandpaper to achieve surface homogeneity. The test procedure was as follows:

1. Samples were soaked in brine, and a 10 μ L kerosene droplet was placed on the rock surface using a micro syringe.
2. After the droplet stabilized, images were recorded using contact angle measurement tools, and initial angles were computed with dedicated software.
3. Taking out the rock, and drying it with an air-laid paper.
4. Rock was then immersed in the CND, then a micro syringe was applied again to drop 10 μ L droplet of kerosene to the rock surface.
5. After the kerosene droplet was stable, a picture was captured again by the contact angle equipment, and contact angle was measured and compared to the initial contact angle.

6. Same steps were repeated from (1) to (6) for rock B, except the immersed liquid is brine in step (5).

Imbibition Test:

1. Place rock sample C into an Amott cell and inject brine until the liquid reaches the marked line on the cell.
2. Place rock sample D into an Amott cell and inject CND until the liquid reaches the marked line on the cell.

Record the oil–water interface at different time points until no further changes are observed in the interface.

3. Core Flow Testing Experiment

Due to the extremely high compactness of the prepared core samples, which made it difficult to conduct core flow experiments, two other cores with higher permeability (0.7 mD) were selected for the experiment.

- (1) Core sample E was subjected to vacuum pumping for 12 h and saturated with brine.
- (2) For wettability modification, a kerosene blend with a 1.5 wt. % oleic acid concentration was employed to displace the core sample for a duration corresponding to over 10 pore volumes (PV). Subsequently, pure kerosene was used for displacement to remove the oleic acid, preventing it from affecting the experimental results.
- (3) CND was injected into the rock in a reverse manner to simulate the invasion of fracturing fluid.
- (4) Steps (1) and (2) were repeated for rock sample F, followed by the reverse injection of brine into the rock for comparison with CND.

During the experiment, the pressure difference as well as the volumes of water and oil were monitored, with the flow rate consistently maintained at 0.05 mL/min throughout the process.

Pressure Transmission Test (PTT):

- (1) The rock was vacuum-treated and then saturated with brine to ensure complete saturation.
- (2) A single rock slice was placed into a specialized core holder to ensure system sealing. The dead volume was then vacuum-treated for 5 min to prevent air interference.
- (3) Kerosene was injected into the downstream until the downstream pressure reached the specified value. After displacing for a long time, the top valve was closed and recording the pressure until it equilibrated with the down value.
- (4) The top valve was opened, and the top part was vacuum-treated for 5 min. The down valve was then opened until the down value dropped to 0.05 MPa. CND was injected into the top part until the value equaled 0.6 MPa. Closing both top and down valves, and pressure changes over time were recorded until equilibrium was achieved.
- (5) The top and down valves were reopened, and the system was vacuum-treated for 5 min. Kerosene was again injected into the down part while maintaining a constant downstream value of 0.6 MPa. After displacing for a long time, the top was closed, and the top value was monitored until equilibrium with the down value was reached.
- (6) Steps (1) to (5) were repeated, with brine replacing the simulated fracturing fluid (CND) in step (4). Finally, the results of the two sets of experiments were compared and analyzed.

4. Result and Discussion

Contact Angle Test

Different wettability characteristics are reflected by variations in the liquid–solid contact angle. Contact angle values were obtained via oil droplet measurements. When a

rock is immersed in an aqueous solution and a drop of kerosene is placed on the bottom of its surface: if the contact angle is $>105^\circ$, the rock is water-wet; if it is between 75° and 105° , it is neutrally wet; if it is $<75^\circ$, it is oil-wet.

After spontaneous imbibition with oleic acid, Rock A exhibited an average contact angle of 49.8° (Figure 5 left) and Rock B 44.9° (Figure 6 left), indicating that both rock surfaces showed oil-wet characteristics. After treatment with CND, Rock A's average contact angle reached 142.7° (Figure 5 right), indicating that its wettability had changed from oil-wet to water-wet. This may be due to the adsorption of surfactants in CND on the rock surface, altering its preferential wettability from oil-wetting to water-wetting. Rock B's average contact angle was 64.4° (Figure 6 right), indicating that it remained oil-wet because the brine could not change its wettability. The contact angle increases because the low-salinity water alters rock wettability toward hydrophilicity by reducing the solid-liquid interfacial tension, dissolving adsorbed high-valence ions on the rock surface, and enhancing the exposure of polar hydrophilic groups.

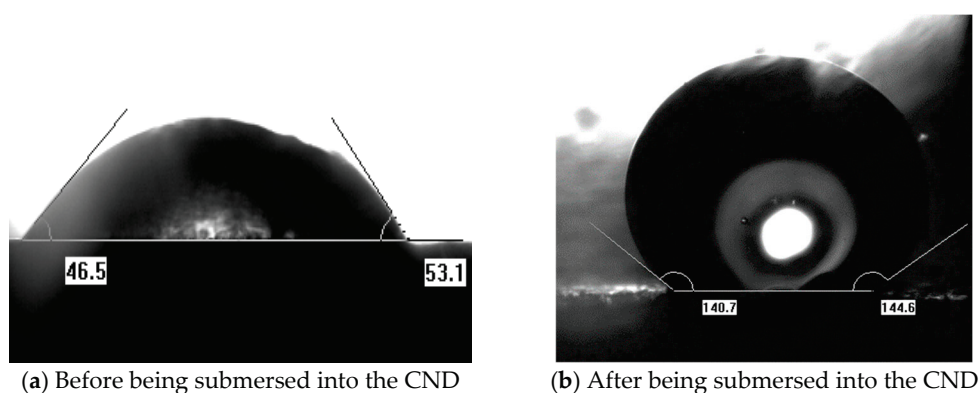


Figure 5. Before and after being submersed into the CND.

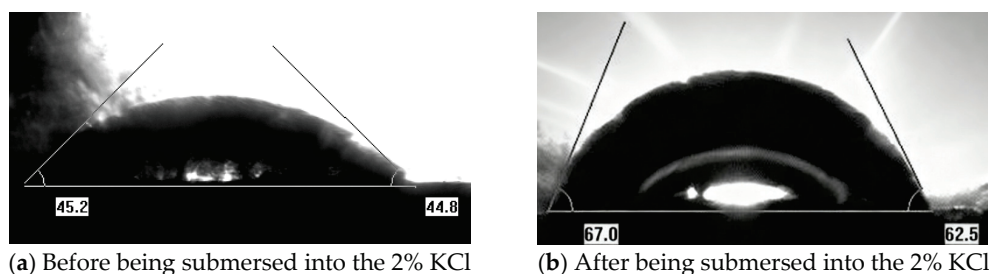


Figure 6. Before and after being submersed into the 2% KCl.

Adhesion between the stone surface and liquid is the resistance during flowing; the adhesion W_n is calculated as the following equation.

$$W_n = \gamma_{ol}(1 + \cos \theta) \quad (1)$$

During the hydraulic fracturing process, some tight oil reservoirs exhibit an initial oil-wet wettability, with contact angles less than 90° . After the injection of CND, the interfacial tension decreases on one hand; on the other hand, the oil-wet reservoir transforms into a water-wet state, with contact angles increasing to values greater than 90° . Consequently, the adhesion force decreases, making it easier for the oil to detach from the rock surface.

5. Spontaneous Imbibition

As shown in Figure 7, the ultimate imbibition recovery of brine reached a maximum value of 22% at 50,000 min. The contact angle test indicated that the rock surface was oil-

wet, while the imbibition test suggested that some pores remained water-wet. These two results implied that the wettability of the Jimsar rock was mixed-wet. By 50,000 min, CND achieved a maximum imbibition recovery of 51%, 29% higher than brine. The difference in oil displacement performance stems mainly from CND-induced wettability changes, which enhance water-driven oil recovery, as the treated rock showed enhanced ability to displace oil compared to brine-treated samples. The driving force for imbibition is capillary force. If the rock wettability is oil-wet, the capillary force will generate resistance, and imbibition will not occur spontaneously; conversely, if the rock wettability is water-wet, the oil will be replaced by water after placing the rock in water. CND can change the wettability from oil-wet to water-wet, thus allowing imbibition to occur and extract more oil. This result is consistent with the observations from the contact angle test. Additionally, Figure 8 shows that the imbibition of both rocks almost ceased at 50,000 min (34.7 days), which is a time-consuming process. Compared to the result of Li et al. [53], the imbibition period for these two rocks is extended. Li et al. conducted the experiment for 120 h, which is less than our experiments, and the permeability is higher. Properties of rock can help explain this phenomena; due to the lower permeability, the flow resistance is considerable, and the explanation is in agreement with the result of Sheng [54] and Yang [55].

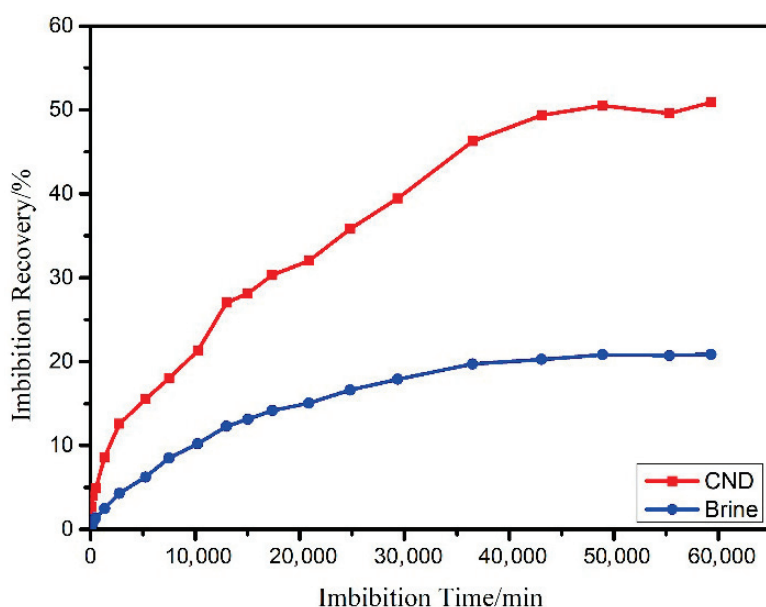


Figure 7. The imbibition curve with CND and brine.

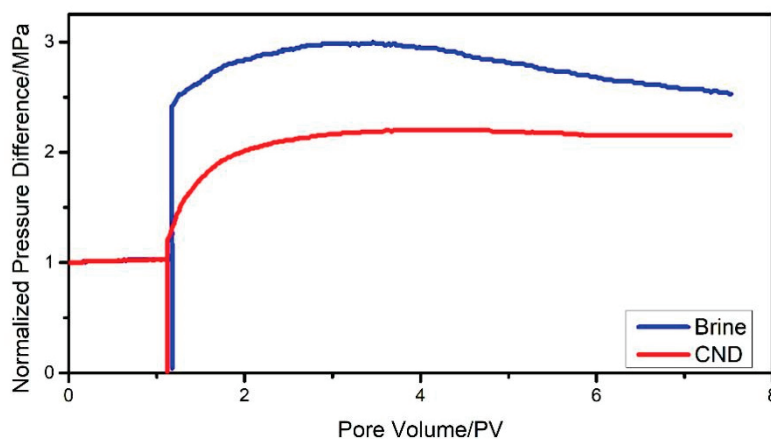


Figure 8. The pressure difference between CND and brine.

Core Flooding Test

As shown in Figure 8, to compare the pressure differences between CND and brine, the study normalized the initial permeability. When injecting CND into the rock, the displacement pressure was 1.2 MPa, whereas it reached 2.5 MPa for brine injection. The experimental results demonstrate that CND can effectively reduce flow resistance.

During the shut-in period, the extremely high pressure environment in hydraulic fractures and connected natural fractures causes fracturing fluid to leak off into the rock matrix. Flow resistance becomes crucial in this post-fracturing shut-in phase. Lower resistance not only offers potential for energy savings but also enables the fracturing fluid to propagate farther, significantly increasing its contact area with crude oil. This expanded effective contact area facilitates pressure wave propagation over greater distances, which helps extend the economic production cycle. Moreover, the enhanced contact between crude oil and fracturing fluid improves spontaneous imbibition efficiency, thereby displacing more oil. Due to its low interfacial tension characteristics, CND reduces flow resistance, resulting in a smaller pressure drop compared to brine. The pressure drop curve morphology in the second step also reflects wettability alteration. During two-phase spontaneous imbibition, when the wetting phase displaces the non-wetting phase, the pressure drop trend shows an “initial rise followed by stabilization” pattern. Conversely, when the non-wetting phase displaces the wetting phase, the trend exhibits an “initial rise followed by decline”. In this study, both core samples were first treated with oleic acid to achieve oil-wet conditions, then saturated with kerosene (which cannot alter rock wettability). In the second step, the pressure drop trend of CND aqueous solution matched the “wetting phase displacing non-wetting phase” characteristic, indicating the rock’s wettability had changed from oil-wet to water-wet. Correspondingly, the brine’s pressure drop trend in the second step followed the “non-wetting phase displacing wetting phase” pattern, confirming the rock remained oil-wet. These results verify that CND can convert oil-wet rock to water-wet, consistent with findings from both contact angle measurements and spontaneous imbibition experiments.

Test of Reservoir Pressure Enhancement

Upstream chamber in the PTT equipment is applied to simulate the fracture after hydraulic fracturing, while downstream chamber is applied to simulate the reservoir pore volume. As shown in Figure 9, the upstream pressure has decreased from 0.6 MPa to 0.11 MPa after closing the valve in the CND invasion experiment, the variation in upstream pressure is 0.49 MPa; while the downstream pressure has increased from 0.05 MPa to 0.11 MPa, the variation in downstream pressure is 0.06 MPa. In addition, the whole process lasts for 15 min. The upstream pressure has decreased from 0.6 MPa to 0.07 MPa in the brine invasion experiment, the variation in upstream pressure is 0.53 MPa, the downstream pressure has increased from 0.05 MPa to 0.07 MPa, the variation in downstream pressure is 0.02 MPa, and the whole process lasts for 80 min.

CND’s final equilibrium pressure was 57% higher than brine, a finding associated with its lower interfacial tension (3 mN/m vs. 34 mN/m for brine), due to the surfactant in the CND, which can reduce the IFT. This reduced IFT minimizes flow resistance. Additionally, CND altered the rock from mixed-wet to water-wet, which further boosted pressure transmission efficiency. The pressure of downstream could represent the reservoir pressure, which makes us conclude that CND can enhance the reservoir pressure. The result implies that surfactants and nanofluid are a crucial part in fracturing fluid, which can not only enhance the oil recovery, but also benefit enhancing reservoir energy. In addition, the balanced time for CND is 19% of brine, which demonstrates that the shorter shut-in period for enhancing reservoir energy is demanded after adding CND. To the best of our knowledge, longer shut-in time can reduce the economic benefit. Thus, CND could help

enhance the revenue from another perspective. CND reduces interfacial tension (3 mN/m) and reverses wettability, increasing capillary driving force (per Young–Laplace equation) and reducing interfacial energy consumption. This enables fracturing fluid to penetrate deeper and store more elastic energy, differing from simple pressure transmission. PTT results show CND's equilibrium pressure is 57% higher than brine, confirming genuine formation energy enhancement.

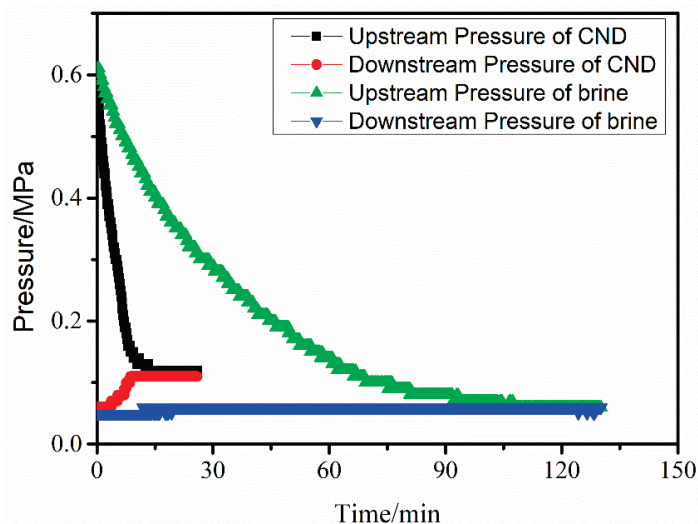


Figure 9. The depletion curve between CND and brine.

To further quantitatively confirm energized extent of CND and brine, energized range (ΔE) is defined, which means improved dimensionless pressure while decreased per unit of pressure during shut-in period.

$$\Delta E = \Delta P'_I / \Delta P_D \quad (2)$$

Dimensionless improved pressure extent: $\Delta P'_I = \Delta P' / \Delta P_D$

Dimensionless decreased pressure extent: $\Delta P_D = \Delta P / P_2$

Improved pressure value: $\Delta P = P_2 - P_1$

Decreased pressure value: $\Delta P' = P_1 - P_0$

Energized speed (ΔF) is defined to show the speed of energized range.

$$\Delta F = \Delta E / T \quad (3)$$

According to Equation (2) and Equation (3), the energized range and the energized speed of CND and brine are calculated, respectively.

Table 2 shows the energized range of CND is 4.08, which is 3.24 times larger than brine (1.26); the energized speed of CND is 0.272, which is 17 times faster than brine (0.016). The calculated results further demonstrate that CND can enhance the reservoir energy and reduce effective shut-in period.

Table 2. Energized range and energized speed of CND and brine.

Type of Fracturing Fluid	Energized Range ΔE	Energized Speed ΔF
CND	4.08	0.272
Brine	1.26	0.016

Permeability Recover Test

The permeability restoration experiment was conducted using PTT equipment. Given the extremely low permeability of tight oil reservoirs, conventional core flow testing equipment struggles to effectively evaluate fluid permeability. Therefore, this study employed an unsteady-state method instead of the traditional steady-flow method to calculate fluid permeability [56,57]. The rock samples used in the experiment were approximately 0.8 cm in length, a design that significantly shortened the experimental cycle. Formation water was first injected into the downstream chamber to simulate pore pressure (P_0); the test fluid was then pumped into the upstream chamber to establish and maintain a higher pressure (P_m). The change in downstream pressure [$P(l, t)$] was continuously monitored until it stabilized. Figure 10 illustrates the pressure change before and after CND invasion. Permeability was calculated using Equation (4), where the λ value was derived from Equation (5). Specifically, data from the stable transition period of downstream pressure were selected to plot a dimensionless pressure ($\frac{P_m - P(L, t)}{P_m - P_0}$) vs. time curve (as shown in Figure 11). The slope of this curve corresponds to the λ value. Detailed calculation methods can be found in the research by Liang et al. [40].

$$K = \lambda \mu C V L / A \quad (4)$$

$$\lambda = \frac{P_m - P(L, t)}{P_m - P_0} / t \quad (5)$$

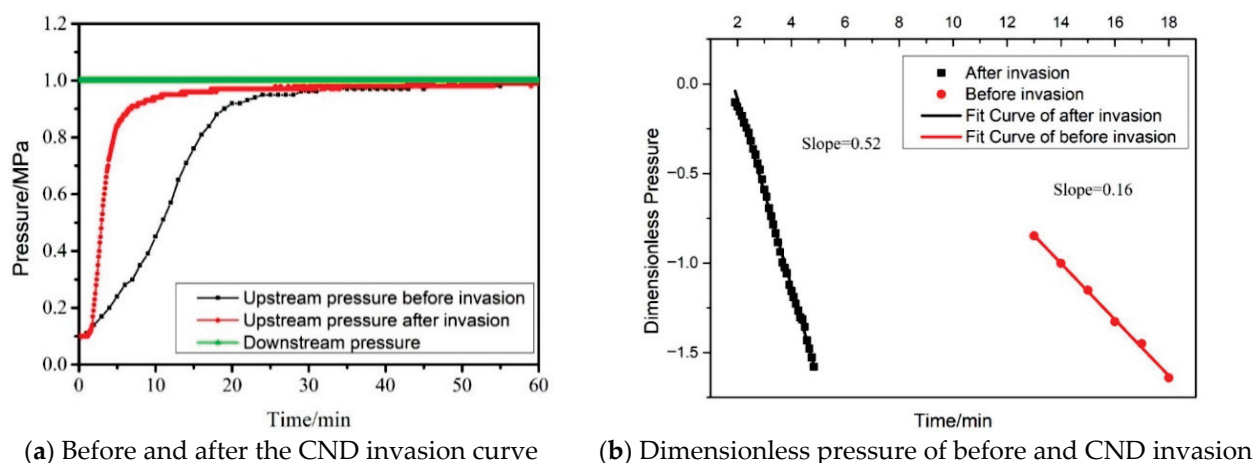


Figure 10. Curves of pressure and dimensionless pressure before and after CND intrusion.

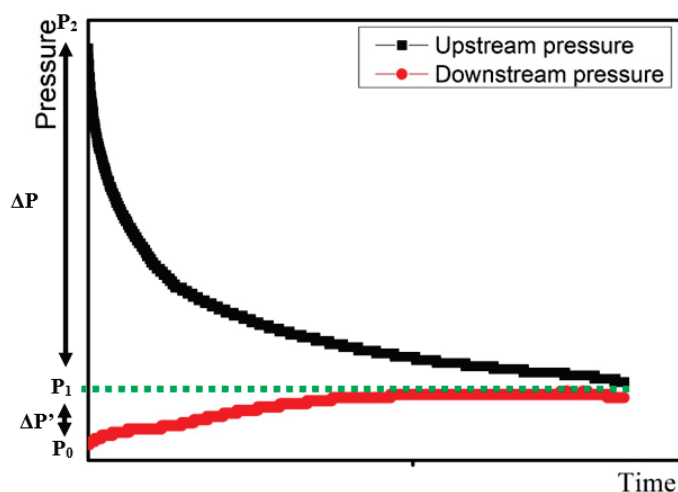


Figure 11. Schematic diagram of depletion.

Figure 10 shows the pressure and dimensionless pressure variations before and after CND invasion into the rock slice. Figure 12 presents the corresponding pressure and dimensionless pressure changes before and after brine invasion. The calculated slopes and permeability results are summarized in Table 3.

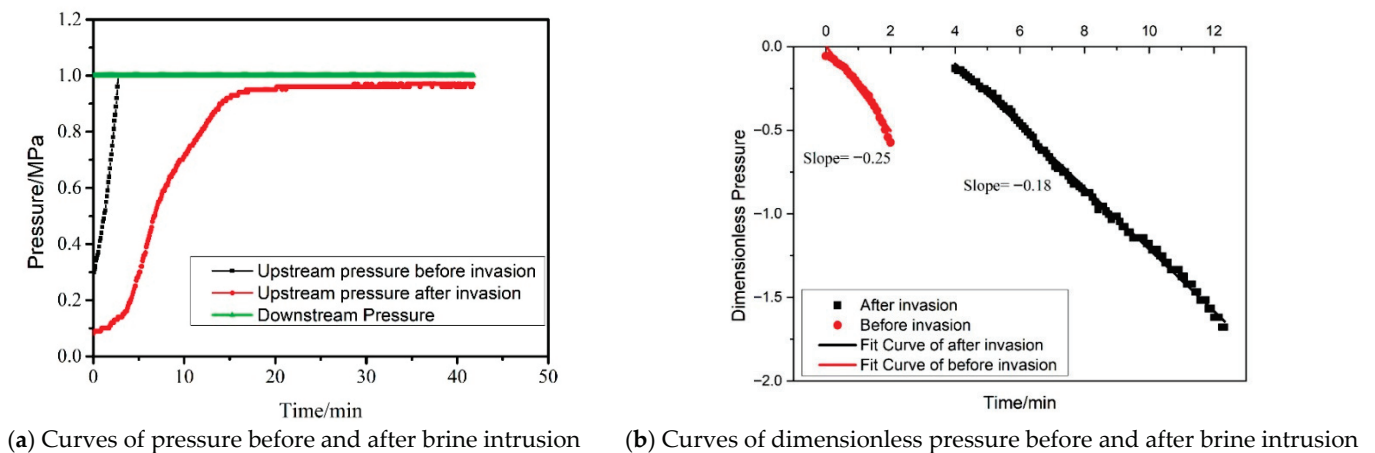


Figure 12. Curves of pressure and dimensionless pressure before and after brine intrusion.

Table 3. Calculated slope and permeability.

Type of Fracturing Fluid	Before Invasion		After Invasion		Permeability Recovery (%)
	Slope	Permeability (μD)	Slope	Permeability (μD)	
CND	0.16	0.19	0.52	0.65	334%
Brine	0.25	0.31	0.18	0.23	73%

Table 3 shows that the initial permeability to oil of two rocks are not much different, which states that the comparison is effective. The result shows that the permeability recovery is 334% after CND invasion, while the permeability recovery is 73% after brine invasion. Compared results demonstrate CND could help increase the production after hydraulic fracturing.

6. Field Application

The CND and common surfactant were applied in two adjacent tight sandstone wells in the Xinjiang oil field in China. The formation pressure and reservoirs conditions are similar for two wells. An amount of 0.1 wt. % CND was added as the fracturing fluid additive during hydraulic fracturing in well #1, while 0.3 wt. % common surfactant was added in well #2. Wells were open to production for 89 days; the result is shown in Figure 13. Over an 89-day production period, well #1 (CND-treated) produced 1750 m³ more oil than well #2 (conventional surfactant-treated). This output increase is likely due to CND's ability to enhance imbibition and minimize permeability impairment, as validated in laboratory tests. Other researchers also proved that production can be enhanced after adding the CND during hydraulic fracturing [45,58–60].

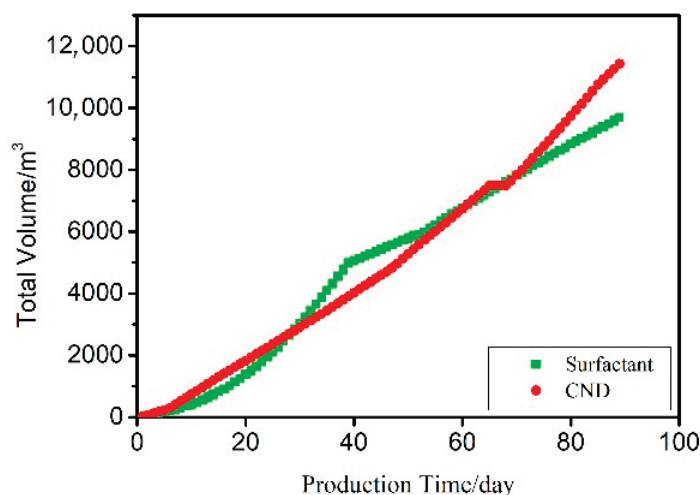


Figure 13. Field comparison between CND and common surfactant.

7. Conclusions

Rapid reservoir energy depletion is a critical challenge in tight oil formation development. While large volumes of fracturing fluid injected during hydraulic fracturing hold potential for enhancing formation energy, oil-wet wettability and high flow resistance prevent fluid penetration into pores and throats, hindering imbibition. This study confirms that Complex Nanofluid Dispersions (CND) effectively addresses these issues through experimental and field validation, with key quantitative outcomes. CND reverses oil-wet rocks to water-wet, boosting spontaneous imbibition recovery to 51%. It reduces flow resistance by 52%, enhances reservoir energy range by 3.24 times, and shortens stabilization time to 19% of brine. Field application in Xinjiang Oilfield shows the CND-treated well produced 1750 m³ more oil than the conventional surfactant-treated well over 89 days. The core mechanisms underlying CND's effectiveness are the synergistic effects of reduced interfacial tension and wettability reversal, which enhance imbibition driving force and reduce flow resistance, achieving both energy retention and productivity improvement.

A limitation of this study is the idealized experimental conditions: cores were collected from the same formation with homogeneous properties, failing to cover the heterogeneity and complex mineral compositions of actual reservoirs. Future research will focus on adaptability studies for multi-property reservoirs to establish a matching model between CND concentration and reservoir properties, numerical simulation optimization coupling imbibition and fracturing processes for precise field parameter design, and long-term stability and compatibility experiments of CND under high-temperature, high-salinity conditions and with other fracturing fluid additives.

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Nomenclature

W_n	the adhesion;
γ_{ol}	the interfacial tension;
θ	the contact angle between stone and oil;
P_2	initial upstream pressure, represents the wellbore pressure after hydraulic fracturing;
P_1	final balanced pressure, represents the reservoir pressure after shut-in well for a long period;
P_0	initial downstream pressure, represents the initial reservoir pressure;
T	the period from initial decrease time to the ended decrease, min;
λ	dimensionless pressure;
μ	liquid viscosity;
C	compressibility of liquid;
V	upstream or downstream sealed chamber;
L	length of rock;
A	cross-sectional area of rock sample;
P_m	initial large pressure.

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Article

Orbital Forcing of Paleohydrology in a Marginal Sea Lacustrine Basin: Mechanisms and Sweet-Spot Implications for Eocene Shale Oil, Bohai Bay Basin

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Abstract

Investigating how climatic and hydrological conditions in ecological resource-enriched zones of marginal seas respond to external forcing, particularly during past greenhouse climates, holds considerable significance for understanding current environmental and resource challenges driven by global warming. In marginal seas, climatic hydrological states, including salinity, redox conditions, and productivity, are key environmental parameters controlling organic matter production, preservation, and ultimately the formation of high-quality shale. Herein, high-resolution cyclostratigraphic and multi-proxy geochemical analyses were conducted on a continuous core from the upper part of Member 4 of the Eocene Shahejie Formation (Es4cu) in Well NY1, Dongying Sag, Bohai Bay Basin. Based on these data, a refined astronomical timescale was accordingly established for the studied interval. By integrating sedimentological observations with multiple proxy indicators, including elemental geochemistry (e.g., Sr/Ba and Ca/Al ratios), organic geochemistry, and mineralogical data, the evolution of climate and paleo-water mass conditions during the study period was reconstructed. Spectral analyses revealed prominent astronomical periodicities in paleosalinity, productivity, and redox proxies, indicating that sedimentation was modulated by cyclic changes in eccentricity, obliquity, and precession. It was hereby proposed that orbital forcing governed periodic shifts in basin hydrology by regulating the intensity and seasonality of the East Asian monsoon. Intervals of enhanced summer monsoon associated with high eccentricity and obliquity were typically accompanied by increased sediment supply and intensified chemical weathering. Increased precipitation and runoff raised the lake level while promoting stronger connectivity with the ocean. In contrast, during weak seasonal monsoon intervals linked to eccentricity minima, basin conditions shifted from humid to arid, characterized by reduced precipitation, lower lake level, decreased sediment supply, and a concomitant decline in proxies for water salinity. The present results demonstrated orbital forcing as a primary external driver of cyclical changes in conditions favorable for resource formation in the Eocene lacustrine strata of the Bohai Bay Basin. Overall, this study yields critical paleoclimate evidence and a mechanistic framework for predicting the spatial-temporal distribution of high-quality shale under comparable astronomical-climate boundary conditions.

Keywords: monsoon dynamics; redox conditions; sea-level reconstruction; cyclicity; source rock heterogeneity

1. Introduction

Marginal sea environments form a transitional zone between land and ocean and act as convergence regions characterized by interaction between terrigenous input, oceanic circulation, and atmospheric forcing [1–4]. As a result, they constitute key settings for the generation and accumulation of hydrocarbon resources worldwide [5–7]. Along the continental margin of the western Pacific, marginal sea basins, such as the South China Sea, East China Sea, and Bohai Sea in China, are at the forefront of global hydrocarbon exploration and discovery and underpin major human activities [8–10]. This importance is closely linked to their distinctive land–sea atmosphere climate system. Monsoon circulation, driven by land–sea thermal contrast, is the primary climatic factor controlling material and energy exchange in marginal seas. It not only regulates regional wind stress and air–sea exchange, but also modulates precipitation runoff and freshwater budgets, as well as coastal upwelling and vertical mixing intensity. Consequently, marginal sea environments are highly sensitive to climate-driven changes in sea level, freshwater input, and evaporation across multiple timescales [11–13]. Solar radiation is the primary driver of the climate system. Over long timescales, quasi-periodic variations in the Earth’s orbital parameters redistribute incoming insolation, which is further amplified in coupled land–sea systems with pronounced topographic asymmetry, enhancing the imbalance in radiative heating and associated momentum. Such effects can, in turn, modulate the dynamical state of Earth’s rotation on geological timescales, ultimately expressed as changes in the intensity and spatial configuration of monsoonal circulation [14]. Therefore, elucidating the effects of monsoon variability on environmental and ecological dynamics in marginal sea systems is crucial for understanding the mechanisms of resource enrichment and delineating the development patterns and resource potential of high-quality mudstone and shale under such climatic conditions [15–17].

As a Cenozoic intracontinental rift basin in eastern China adjacent to the Bohai Sea (Figure 1) [18,19], the Bohai Bay Basin contains abundant Paleogene fluvial, lacustrine, and marginal-marine to transitional deposits, including prolific source rocks [10,20]. Effects of marine incursions on the basin during the Paleogene, therefore, remain highly debated. Based on assessments of tectono-paleogeography, paleosalinity/alkalinity proxies, and paleontological evidence [21], scholars argued that the intra-basin lake was intermittently connected with the open ocean via the TanLu Fault Zone and additional fault systems located ~ approximately 100 km east of the belt [22], with three distinct episodes of direct seawater incursion taking place during deposition of the Shahejie Formation. In contrast, Li et al. [23] re-evaluated the marine influence in the Dongying Depression using mineralogical, isotopic, and facies records, proposing that key features in the Shahejie succession did not arise from direct incursions. Instead, they attributed the signals to (1) subsurface seepage of seawater across topographic barriers separating the marine and lacustrine systems and to (2) sea-level-driven modulation of groundwater level, which together generated a feedback regulation. These sedimentological and geochemical studies indicated that the Shahejie deposition within this coupled sea–lake setting was highly sensitive to hydroclimatic variability [24–26]. Notably, spectral analysis of salinity-related proxies for the Es3x Member in the Dongying Lake Basin conducted by Wei et al. [10] revealed clear astronomical pacing, implying that orbital forcing periodically influenced lacustrine sedimentation through variations in marine input. Likewise, Zhang et al. [27] linked monsoon-driven

chemical weathering intensity derived from major and trace element records in the lower Es3 interval of the Lijin Sag to eccentricity-scale orbital cycles. Accordingly, continuous, high-resolution terrestrial archives coupled with high signal-to-noise paleoclimate proxies forged an effective foundation for identifying orbitally forced climate variability [28–30]. Collectively, these lines of evidence suggested that variations in the strength of the land–sea monsoon circulation modulated the expression of potential marine influence, offering an exceptional window into marginal sea proximal lacustrine systems’ response to orbitally paced hydroclimate changes [31–33].

Debate nonetheless persists over the manner in which astronomical forcing modulated regional hydroclimate processes during the early-middle Eocene. Some studies ascribe climate variability in eastern China primarily to the ~100 kyr eccentricity cycle [34], whereas others emphasize the dominant roles of >1 Myr-long period eccentricity and obliquity cycles [35], or suggest that late Eocene hydroclimate change in western China was controlled by strong ~100 kyr and ~400 kyr eccentricity cycles [36,37]. These divergent interpretations hinder precise correlations among Eocene climate events and prevent a unified understanding of the underlying climate dynamics. Therefore, the mechanisms by which orbital forcing influences seasonality and produces hydroclimate responses at orbital timescales warrant additional evidence, rendering it necessarily important to better constrain monsoon dynamics under a marginal sea setting.

To this end, this study focused on the middle-late Eocene, a critical interval when the East Asian monsoon began to expand northward [38–40], while the Antarctic ice sheet had not yet undergone major expansion [41,42]. An integrated, multi-proxy cyclostratigraphic analysis was conducted on the continuous subsurface record from the upper part of Member 4 of the Shahejie Formation (Es4cu) in Well NY1, Dongying Sag. The core was recovered from a shallow- to semi-deep-lacustrine setting, where autogenic noise from the source-to-sink system was expected to be minimal [43,44]. This setting enabled the construction of a novel, high-resolution astronomical timescale for the middle Eocene. Based on the astronomically tuned stratigraphy, sedimentary petrology, geochemistry, and cyclostratigraphic analyses to identify multi-order climate cyclicity were recorded in the Es4cu succession. Cross-scale cyclicity was compared against key paleoclimatic proxies and variations to assess the coupled evolution of hydroclimatic conditions in this marginal sea-linked affiliated system and their orbital forcing responses.

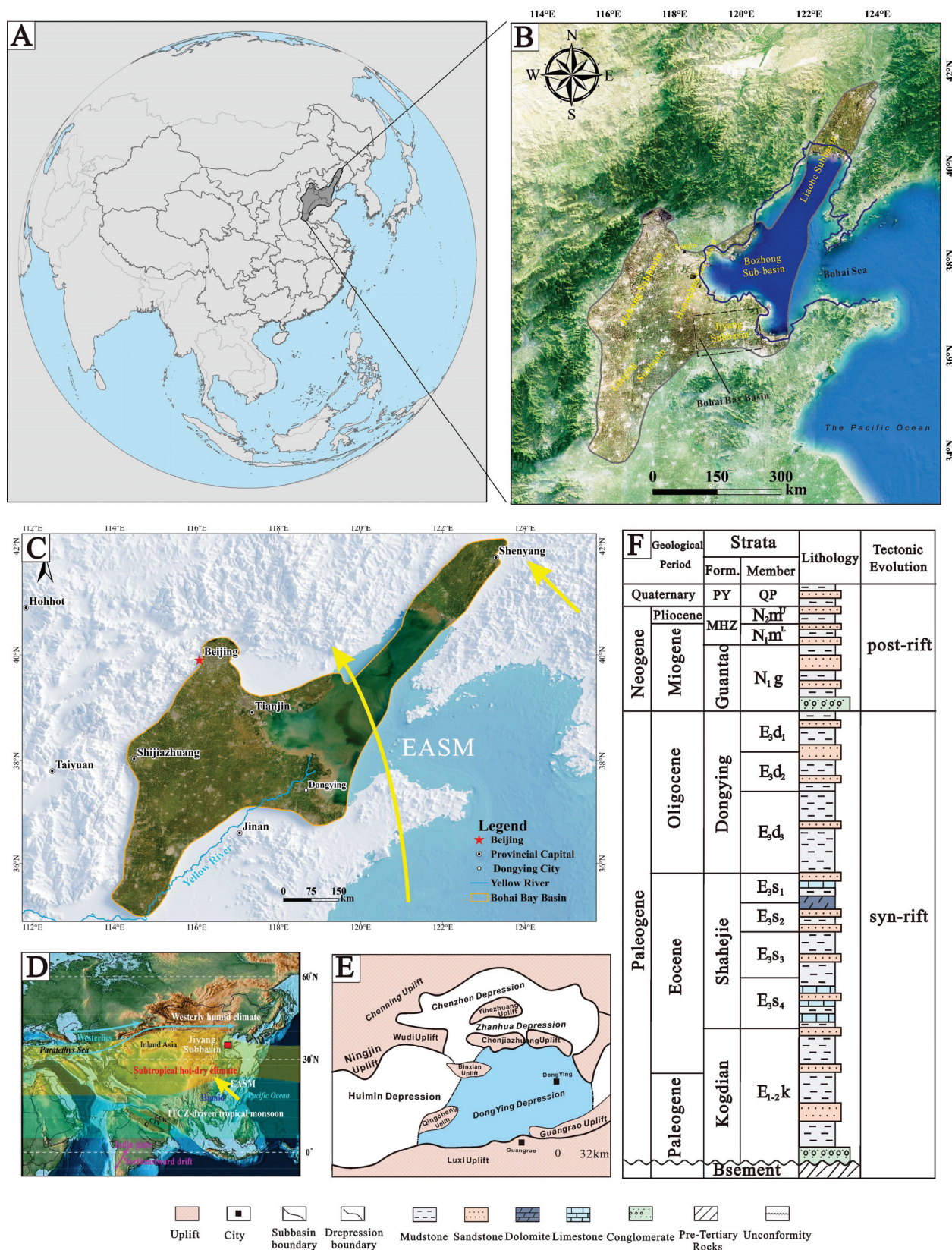


Figure 1. Location map of the study area and stratigraphic column of the Dongying Sag. (A,B) Present-day geographic location map of the Jiyang Depression, Bohai Bay Basin; (C) inferred East Asian summer monsoon wind directions (yellow arrows) during the middle-late Eocene, modified from Licht et al. [38] and Meijer et al. [45]; (D) paleogeographic reconstruction for the middle-late Eocene [43], and the atmospheric circulation pattern, modified from [46]; (E) structural characteristics map of the Dongying Sag, modified from Feng et al. [47]; (F) composite stratigraphic column of the Dongying Sag.

2. Geological Settings

The Bohai Bay Basin is located in the eastern part of the North China Craton, between ~35° and 40° N, and is a Mesozoic Cenozoic intracontinental rift basin (Figure 1). Its Cenozoic tectonic evolution comprises two main stages: a rifting stage, followed by a post-rift (sag) stage [48,49]. The basin preserves an exceptionally thick Paleogene continental succession, with its geographic position remaining largely unchanged over the past ~65 Ma. The regional land–sea configuration during the middle-late Eocene was broadly similar to the modern setting [19], affording an important opportunity to investigate past and future climate states [50–52].

The Dongying Sag is located in the southern part of the Jiyang Depression, Bohai Bay Basin. Spanning approximately 5700 km², the sag ranks among the most hydrocarbon-prosperous in the basin. Cenozoic strata are continuously developed, and the Paleogene syn-rift succession exceeds 7000 m in thickness [53–55]. It mainly comprises lacustrine deposits of the Kongdian, Shahejie, and Dongying formations (Figure 1F). This syn-rift succession can be further divided into the following four sub-stages: (1) initial rifting (Kongdian Formation; early Paleocene to early Eocene); (2) late initial rifting (Member 4 of the Shahejie Formation; early to middle Eocene); (3) main rifting (Member 3 of the Shahejie Formation; middle to late Eocene); and (4) rift waning (Member 2 of the Shahejie Formation to the Dongying Formation; late Eocene to late Oligocene) [36,47,56]. Overall, the Paleogene stratigraphic succession is extensively regarded as continuously deposited, involving no major depositional hiatus. During the early Eocene (Kongdian Formation to the lower sub-member of Member 4), the regional climate was relatively arid, and deposition was dominated by floodplain–shallow lake and seasonal lake facies characterized by “red-gray” assemblages [57–59]. As deposition progressed into the upper sub-member of Member 4, the lake expanded, salinity increased, and the system evolved into a brackish-to-saline environment. In the western part of the sag, large lacustrine carbonate reef shoal systems developed, possibly attributed to the relatively warm climate and the influence of the paleo-East Asian monsoon. During deposition of Member 3, the lake deepened further, with maximum paleo-water depths estimated to exceed 550 m. Salinity gradually decreased, transitioning toward a freshwater system [60–62]. Thus, the depositional environment experienced a full shift from arid to humid conditions and from saline to freshwater waters, producing thick and continuous deep-lacustrine dark mudstone, shale, and oil shale. The Es4u interval, the focus of this study, was deposited in a deep-lake setting during the syn-rift stage. Relatively deep water and elevated salinity facilitated the formation and preservation of organic-rich black shale, and these deposits provide a continuous archive of orbital-scale paleoclimate and paleoenvironmental variability [63–65].

3. Methodology

3.1. Core and Paleoclimate Multi-Proxy Indicators

To evaluate shale oil potential and investigate paleoclimate variability, Sinopec drilled multiple cored wells in the Dongying Sag (e.g., wells FY1 and NY1, Figure 2). Continuous and complete cores, together with supporting wireline logs and high-resolution core images, were recovered from the Es3l and Es4u intervals, providing an exceptional archive for high-resolution paleoclimate studies.

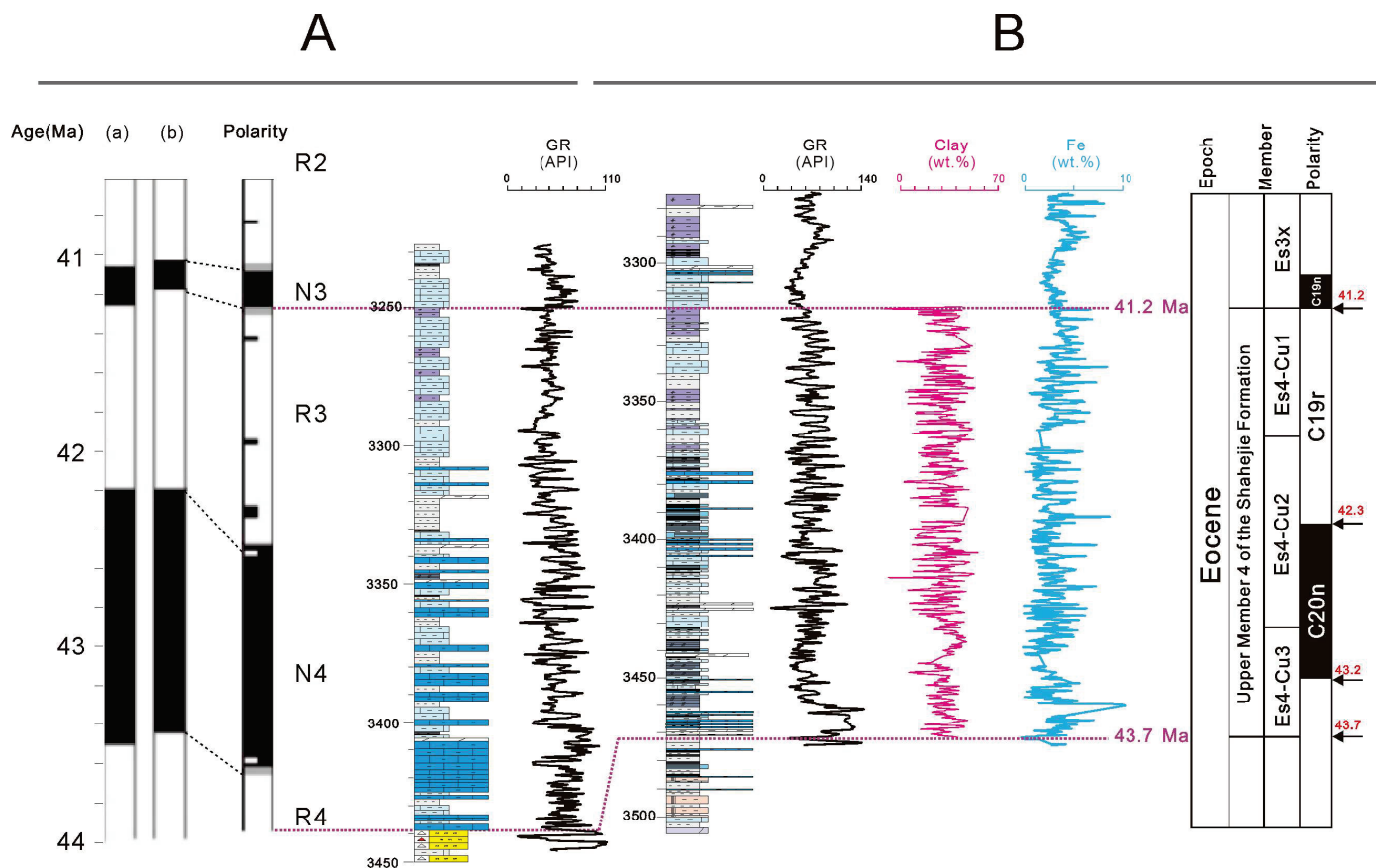


Figure 2. Magnetostratigraphy and proxy data of the NY1 well in the Dongying Sag. (A) The geomagnetic polarity timescale of the FY1 well in the Dongying Sag, modified from Ma et al. [33]: (a) from Westerhold et al. [66] and (b) from GPTS2020 [67]; (B) reinterpreted magnetostratigraphy of the NY1 well, modified from Jin et al. [30] and proxy series for cyclostratigraphic analysis: gamma ray, clay content (wt.%), and Fe (iron) content series (wt.%) from the NY1 well.

In Well NY1, coring was conducted from 3295 to 3498 m, with a drilled interval of 203 m. The recovered core length is 185.22 m, corresponding to a recovery rate of 91%. The natural gamma ray log of the upper part of Es4cu spans 3316–3471 m and can be subdivided into three sub-intervals [68] (Figure 2B). Six main lithologies occur within this interval: mudstone, calcareous mudstone, calcareous shale, dolomitic limestone, argillaceous limestone, and argillaceous siltstone [69] (Figure 2). A total of 78 core samples were collected. A Bruker portable X-ray fluorescence (XRF) spectrometer was employed for in situ measurements on clean, flat core surfaces. Analyses were performed at an operating voltage of 10 kV and a current of 0.15 mA, involving a counting time of 60 s per spot. The sampling interval was 1–4 cm, locally tightened in selected intervals to increase resolution. Results are reported as oxide wt% for major elements and as ppm for selected trace elements. More than 20 elements, including Al, Mg, Fe, Ca, K, U, Zr, Ti, Mn, Ba, and Sr, were measured. Elemental concentrations determined by XRF were generally precise, and the measurement reliability exceeded the 95.4% confidence level [70]. Nevertheless, pXRF datasets are generally regarded as semi-quantitative in nature. Calibration against conventional geochemical analyses consistently yields weaker correlations for low-abundance and/or poorly detectable elements. To improve accuracy, the XRF dataset was hereby normalized to conservative elements (Si and Al) to remove the influence of detrital input, following the evaluation of pXRF calibration strategies by Gregory et al. [71].

3.2. Time-Series Analysis

All astronomical cyclostratigraphic analyses were performed using Acycle V2.7 [72] to systematically identify, extract, and calibrate orbital-scale climate signals from multiple proxy records. The workflow followed four steps: (1) data preprocessing, (2) spectral analysis, (3) optimization of sedimentation rates, and (4) filtering and tuning [73,74].

First, the raw data of natural gamma ray (GR), clay content, and Fe element were preprocessed, including the removal of outliers, equally spaced interpolation, and elimination of long-term trends using LOWESS smoothing. Subsequently, the multitaper method (MTM) power spectral analysis was applied [75,76], and fast Fourier transform (FFT) power spectra were utilized to delve into frequency evolution and identify dominant frequencies in the sequences [72]. The significance of spectral peaks was evaluated against a red-noise background ($AR_{(1)}$), and the mean, 90%, 95%, and 99% confidence levels were determined. Based on the candidate orbital frequencies, the correlation coefficient method was used to compare the data spectra with the theoretical spectrum derived from the La2010 astronomical solution, thereby determining the optimal sedimentation rate and testing the null hypothesis of no orbital forcing. eCOCO was further employed to track downcore variations in sedimentation rate and to evaluate robustness [76]. Finally, using the La2010d high-precision theoretical astronomical solution as the benchmark, the significant spectral peaks extracted from the spectrum analysis were observed to be attributed to specific orbital parameters (eccentricity, obliquity, and precession). On this basis, Gaussian bandpass filtering was adopted to isolate the eccentricity and obliquity cycle signals within the target frequency bands from the proxy index series. By integrating the filtered output with visual inspection of cyclic characteristics, the ~405 kyr long eccentricity cycle was identified and anchored. Subsequently, the depth domain was converted into the time domain, ultimately constructing the floating astronomical timescale required for this study.

In recent years, numerous investigations have sought to establish a chronological framework for the Paleogene strata of the Bohai Bay Basin. Such frameworks, however, are often constrained by low temporal resolution and ambiguous validity. In the absence of absolute age tie points, the majority of existing astronomical timescales remain highly dependent on the selection of the reference timescale. Despite discrepancies between the GPTS2020 and the Westerhold et al. [66,77] timescales regarding the ages of several polarity chrons, the two show closely consistent boundary ages (within ± 0.6 Ma) for the transitions identified at C18n.1n/C18n.1r and C19n/C19r (Figure 2A). Based on the updated polarity times provided by GPTS2020, Shi et al. [28] conducted a systematic magnetostratigraphic study on the FY1 well within the study area and established an age model refined through linear interpolation tuning. Concurrently, Jin et al. [30] established an astronomical timescale for the interval E3x–E4u in the study area using other proxy indicators, comparing it with the timescale established by Shi et al. [28,29,70]. This integrated work ultimately yielded a floating astronomical timescale spanning 39.26–43.68 Ma. It was further noted that the E3x–E4u boundary approximately corresponded to the base of C19n, thereby providing a reliable chronological framework for this study's in-depth analysis of middle Eocene climate dynamics.

3.3. Sedimentary Noise Modeling

Li et al. [78] pioneered the application of the sedimentary noise model to lacustrine basin settings, successfully revealing the intrinsic link between lake-level changes and million-year-scale cycles. Subsequently, the theoretical work further clarified that, despite differences in study carriers (marine versus lacustrine), the core mechanisms driving sedimentary noise variations and recording their cyclicity were fundamentally similar. Multiple independent studies within the research area have further validated and advanced the ap-

plicability and robustness of the sedimentary noise model for quantitatively reconstructing paleo lake levels [79]. The DYNOT model uses orbitally tuned paleoclimate proxy records to semi-quantitatively recover the strength of non-orbital disturbances, such as bioturbation, tides, and storms. The inferred disturbance intensity is closely related to paleo-water depth. The ρ_1 model employs the lag-1 autocorrelation coefficient as an independent noise metric for relative lake-level change [80]. Both models reveal a strong response to lake-level fluctuations. Therefore, they can be jointly applied to invert paleo-water depth and reconstruct million-year-scale eustatic lake-level variations. Herein, uncertainty was evaluated using a 300–500 kyr sliding window and 20,000 Monte Carlo simulations implemented in Acycle V2.7 [72,76,78].

4. Results

4.1. Mineral Composition

XRD results indicate that shales from the upper sub-member of Es4cu of the Shahejie Formation in the Dongying Sag are mainly composed of carbonate minerals (Figure 3), clay minerals, and quartz, with minor plagioclase, K feldspar, and pyrite. Among the samples analyzed, 55% possess carbonate content >40 wt.%. Calcite is the dominant mineral (mean 38.39 wt.%). Dolomite contents are variable and show pronounced enrichments near the base of the Es4cu interval. Siderite is minor (<3 wt.%), likely reflecting the relatively small lake basin area in the Dongying Sag during the Eocene and strong climatic control [81]. Clay minerals have an average content of ~21.2 wt.% and are dominated by illite, which accounts for an average of 83.8% of total clays; illite-smectite mixed layers are also present (mean 16.2%). Quartz is ubiquitous, with contents ranging from 1 to 54 wt.% (mean 22.6%). Plagioclase and pyrite contents vary from 1 to 22 wt.% (mean 3.8%) and 1 to 15 wt.% (mean 2.9 wt.%), respectively.

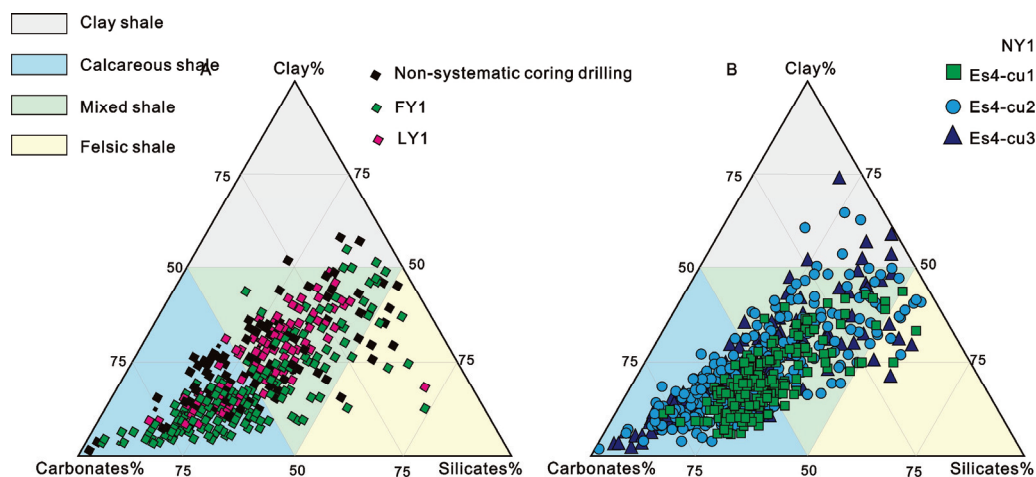


Figure 3. Ternary diagrams of bulk mineral composition (in percentage) of shales from the upper part of the fourth member of the Shahejie Formation in the study area. (A) Data from wells FY1, LY1, and other non-systematically cored wells within the study area; (B) data exclusively from the key Well NY1 of this study.

Overall, mudstones and shales from the Es4cu interval in the Dongying Sag show broadly similar mineralogical compositions, despite spatial differences arising from tectonic settings. The Lijin sub-sag constitutes the deepest and most extensive lacustrine depocenter in the study area; XRD data from Well LY1, herein, reveal elevated clay mineral contents relative to other regional intervals [80], in contrast to carbonate contents that are lower than those recorded in Well NY1.

4.2. Lithofacies

Rocks in the study area are characterized by thick-bedded mudstone and interbedded shale. Based on mineral composition, five lithologies can be identified: silty, clay-rich shale (Figure 4A), laminated calcareous shale (Figure 4B–D), laminated shale with thin gypsiferous interlayers (Figure 4C), massive calcareous shale (Figure 4Q), and bedded calcareous shale (Figure 4J,K). Bioclasts are dominated by algal fragments and ostracod shells. According to differences in the fabric of silt and sand sized detritus, the silty, clay-rich shale can be further subdivided into the following: (1) parallel-laminated, silty, clay-rich massive shale (Figure 4A,M); (2) massive silty shale with convolute lamination (Figure 4B,I,M,N); (3) laminated shale containing lenticular and irregular silty detrital particles (Figure 4A,E); and (4) massive-to-bedded silty muddy mixed rock.

Microscopic petrographic observations and mineralogical characterization (Section 4.1) demonstrate calcite as the most widespread mineral in the area. According to crystal size, calcite can be further classified into coarse crystalline ($>100\ \mu\text{m}$), fine crystalline ($30\text{--}100\ \mu\text{m}$), and cryptocrystalline ($<30\ \mu\text{m}$). Therefore, by integrating mineral composition, sedimentary structures, carbonate crystal size, and mineral assemblages, a three-tier nomenclature scheme [82] was hereby adopted and the study area was classified into eight microfacies/lithofacies (MLs): (1) laminated micritic argillaceous limestone facies; (2) laminated microcrystalline argillaceous limestone facies; (3) laminated coarse crystalline argillaceous limestone facies; (4) laminated mixed mudstone facies; (5) bedded argillaceous limestone facies; (6) bedded calcareous mudstone facies; (7) organic-rich massive mudstone facies; and (8) organic-rich bedded gypsiferous mudstone facies. MLs developed in the study area are detailed below.

1. Laminated micritic argillaceous limestone facies (ML1)

This facies is distinguished by straight, continuous, and parallel laminae (Figure 4B,J). With individual laminae typically measuring $<0.5\ \text{cm}$ in thickness. XRD analyses reveal high calcite abundances in this facies, with concentrations peaking at 76% (and averaging 47%), while dolomite contents are consistently below $<10\%$. The facies contains abundant ostracods, algae, and terrigenous organic matter (Figure 4O,P). Shallow bioturbation structures are commonly tubular and lenticular, cutting across and locally destroying primary lamination. Most burrows are $0.5\text{--}3.2\ \text{cm}$ in diameter and feature clear boundaries; they can be readily distinguished from the host rock by color and infill. Additionally, progradational laminae that intersect or truncate horizontal laminae are locally identified in cores. The horizontal laminae are interpreted to have formed via suspension settling in a quiet deep-lake setting with abundant algae, ostracods, and terrigenous organic matter. In contrast, the progradational laminae likely record depositional modification by turbulence or bottom currents triggered by monsoonal rainfall events. Under the microscope, this facies shows distinct alternating light-dark laminae with good continuity, forming laterally persistent horizontal layers; locally, the laminae display gentle wavy undulations (Figure 5A,B). The light-colored laminae are dominated by micritic calcite. The dark laminae consist of organic-rich, argillaceous laminae and are typically thinner than the calcite-bearing light laminae. Framboidal pyrite aggregates and dispersed organic matter fragments are common within the dark laminae. Bioclasts are frequently concentrated along lamina boundaries. Ostracod distribution differs markedly between the light- and dark-colored laminae. Ostracod abundance in the light laminae reaches $\sim 15\text{--}40\ \text{shells}/\text{cm}^2$, whereas it drops to as low as $0\ \text{shells}/\text{cm}^2$ in the dark laminae. This contrast in ostracod abundance further supports the depositional origin interpretation of the light–dark lamina couplets.

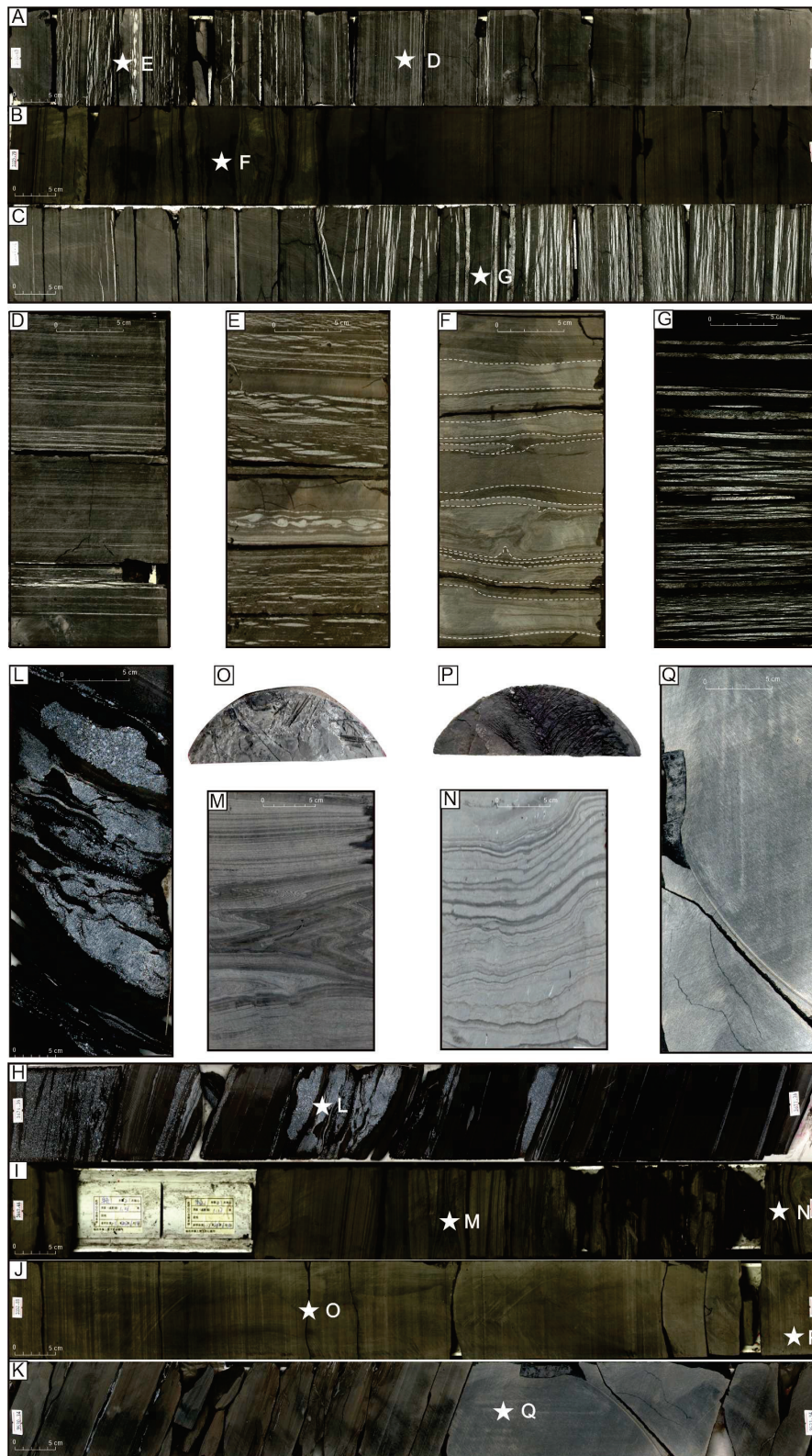


Figure 4. Core characteristics of the upper pure sub-member of the fourth member of the Shahejie Formation (Es4s) in the study area. (A) Core from Well FY1 at the depth of 3170.03–3171.03 m; (B) core from Well FY1 at 3325.79–3326.76 m; (C) core from Well LY1 at 3641.7–3642.7 m; (D–G) enlarged views of the core features at the locations marked by stars in subfigures (A–C); (H) core from Well LY2-1 at 3676.36–3677.36 m; (I) core from Well NY1 at 3649.46–3650.46 m; (J) core from Well NY1 at 3352.81–3353.81 m; (K) core from Well FY1-1 at 3530.34–3531.34 m; (L–Q) enlarged views of the core features at the locations marked by stars in subfigures (H–K).

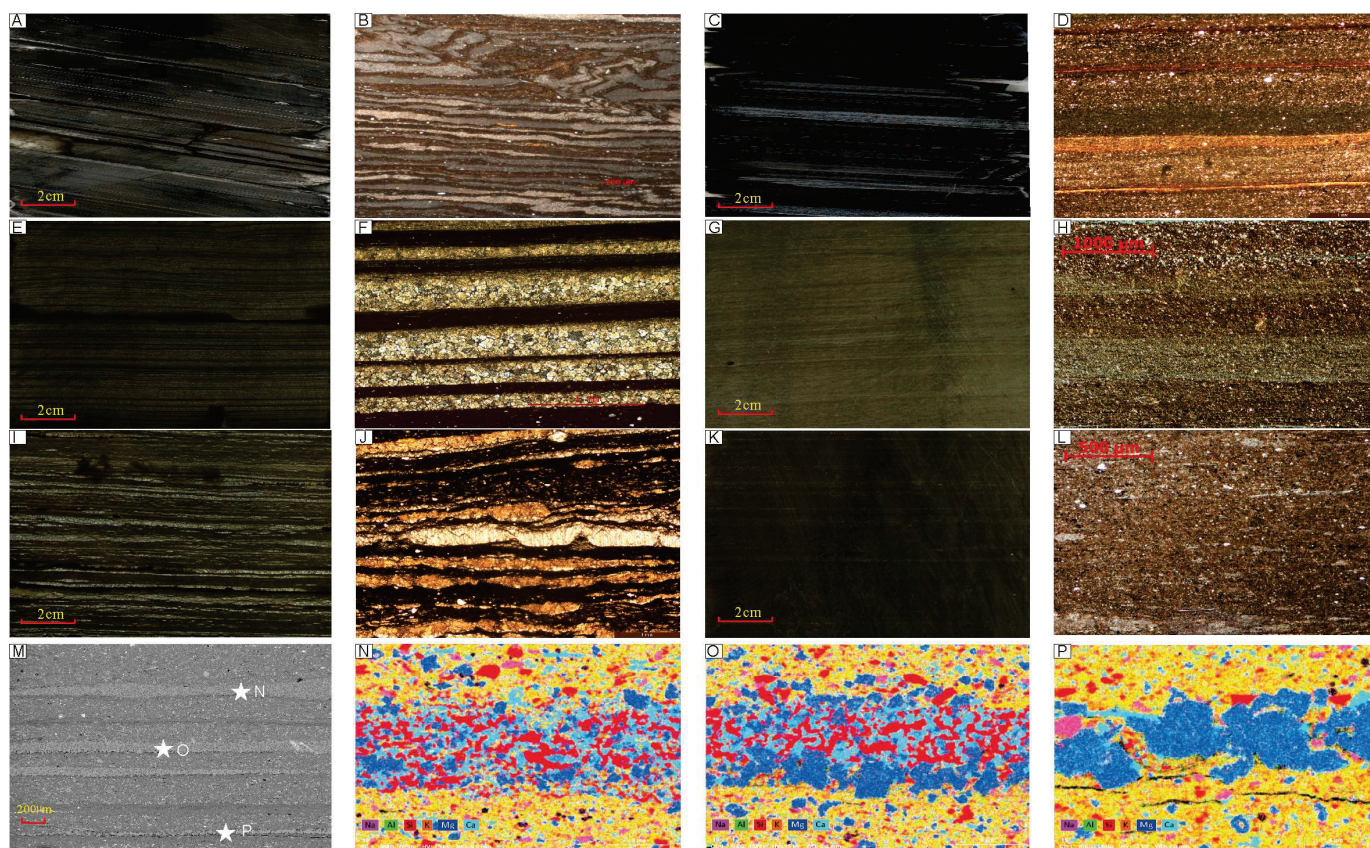


Figure 5. Characteristics of mudstone lithofacies in the upper pure sub-member of the lower fourth member of the Shahejie Formation (Es4cu) in the study area. (A,B) Laminated micritic argillaceous limestone facies, Well FY1-1, 3666 m; (C,D) laminated mixed mudstone facies, Well LY2-1, 4284 m; (E,F) laminated microcrystalline argillaceous limestone facies, Well NY1, 3484 m; (G,H) bedded argillaceous limestone facies, Well NY1, 3316 m; (I,J) laminated coarse crystalline argillaceous limestone facies, Well FY1 HF, 3666 m; (K,L) bedded calcareous mudstone facies, Well NY1, 3339.18 m; (M–P) scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) images of laminated shale, Well FY1-1, 3667.15 m. The star indicates the area analyzed by EDS (element mapping): Si (red), Ca (light blue), Mg (dark blue), Al (green), and K (orange).

2. Laminated mixed mudstone facies (ML2)

This facies is dark gray to gray-black in core and is characterized by continuous, gently micro-wavy lamination (Figure 5C). Stratigraphically, it is primarily concentrated in the upper part of the Es4cu. Microscopic observations reveal alternating light and dark laminae. The light laminae represent a mixed deposition of clay minerals, cryptocrystalline micro-sparry calcite, and terrigenous detritus (Figure 5D). Calcite shows a low degree of recrystallization. The dark laminae are organic-rich clay layers, in which organic matter is evenly mixed with clay. XRD results indicate a ternary mixture of carbonate, clay minerals, and terrigenous detritus, with each endmember accounting for <50%. Carbonate minerals comprise 36–45% (mean 41%), and clay minerals 17–35% (mean 26.5%), with quartz plus feldspar contents being comparable to those of clay minerals.

3. Laminated microcrystalline argillaceous limestone facies (ML3)

This facies is dark gray in core and displays distinct, continuous horizontal laminae on the core surface (Figure 5E). Thin section observations show regular interlayers of organic-rich argillaceous laminae and microcrystalline calcite laminae, with sharp boundaries between adjacent laminae (Figure 5F). Calcite laminae are typically thicker than argillaceous laminae, with calcite occurring primarily as microcrystals exhibiting rhombic, triangular,

and elliptical morphologies. Intercrystalline spaces are filled with organic matter and dispersed pyrite. A small amount of coarse dolomite crystals is also present within the calcite laminae, with grain sizes of 30–50 μm . This facies is rich in organic matter, with total organic carbon (TOC) commonly ranging from 3% to 4%.

4. Bedded argillaceous limestone facies (ML4)

Stratigraphically, this facies commonly alternates with laminated calcareous mudstone (Figure 4J,K). XRD results show reduced carbonate content compared to that in laminated shale, accompanied by increased quartz and clay minerals. In cores, a few horizontal laminae with diffuse boundaries and small thicknesses are observed, together with gently dipping progradational laminae. Thin section observations indicate relatively well-defined bedding. Sedimentary structures such as climbing ripples and low-angle cross-bedding observed in comparable deep-lacustrine settings have previously been attributed to rapid lake-level fluctuations and/or reworking by bottom currents. Observations from modern rivers and Cretaceous lacustrine successions demonstrated that hyperpycnal flows can play a key role in deep-water fine-grained deposition [83,84]. Given that the paleogeographic position of Well NY1 was closer to the deep-water depocenter, these structures are interpreted here as the product of monsoon-related heavy rainfall that generates hyperpycnal flows transporting sediment basinward; upon deposition of the relatively coarser fraction, lateral migration of the residual flow is enhanced, promoting the development of these tractional structures. The fabric is characterized by interbedded and locally mixed distributions of felsic detritus (quartz feldspar), clay minerals, and micritic calcite (Figure 5G,H), exhibiting strong color contrast between adjacent layers. Carbonate minerals are the dominant constituent, with their content being slightly higher than that of terrigenous detritus. Their organic matter abundance is relatively high, with TOC mainly ranging from 2% to 4%, occurring as dispersed enrichment within the rock.

5. Laminated coarse crystalline argillaceous limestone facies (ML5)

This facies exhibits prominent lamination and commonly interbeds with laminated calcareous mudstone. The argillaceous horizontal laminae are mostly straight and continuous, and they contain fibrous columnar or lenticular calcite bands. In the core and thin section, calcite within these bands is mainly fine-to-medium crystalline. The bands vary in length and are typically 0.10–0.7 cm wide, with the long axes of calcite crystals predominantly oriented perpendicular to bedding (Figure 4D,G). Ostracod fossils and fragments are occasionally observed. Microscopically, this facies consists of interlayers of organic-rich argillaceous laminae and calcite laminae. The calcite laminae are relatively thick and are composed of coarse, clean crystals. Calcite is commonly euhedral to subhedral, showing typical dog-tooth crystals (often rhombohedral). These crystals usually grow in tightly packed arrays perpendicular to the lamination surface, or are connected by equigranular crystals. Under fluorescence microscopy, partial calcite exhibits heterogeneous luminescence, suggesting multi-stage cementation (Figure 5I). Organic matter is strongly enriched in the argillaceous laminae, and TOC values reach 3–8% and, displaying high overall abundances.

6. Bedded calcareous mudstone facies (ML6)

At the core scale, this facies is characterized by silty calcareous mudstone and shows laminated to bedded structures; a massive texture is locally developed. Intervals enriched in abundant silt-sized grains display large variations in sedimentary structures and grain size, indicating typical event deposition. These event layers are composed mainly of terrigenous silt detritus with minor broken bioclasts. Bed thickness varies markedly. The bases of beds commonly show erosional, sharp contacts with uneven surfaces, and mud clasts and silty

lithic fragments are clearly visible within the beds. Soft-sediment deformation structures are locally observed (Figure 4H,L). Thin section observations indicate that bedding is expressed by the occurrence of carbonate lenses, the preferred orientation of bioclasts (dominated by ostracods), and the aligned distribution of charcoal fragments (Figure 5L). The rock is composed of a mixed assemblage of clay minerals, feldspar, quartz, and calcite. Calcite occurs as local lenticular bodies, whereas feldspar and quartz grains are predominantly dispersed. Framboidal pyrite is ubiquitous, typically forming clustered aggregates. XRD analyses reveal low carbonate contents, with combined quartz plus feldspar abundances exceeding those of carbonate minerals.

7. Organic-rich massive mudstone facies (ML7)

This facies is sparsely developed in the lower part of the Es4cu. Core observations uncover that lamination is poorly developed and the rock is mainly massive. It is dark gray to black, massive, and well-sorted, and is rich in organic matter. Plant leaf and stem fragments are locally observed (Figure 4K,Q).

8. Organic-rich bedded gypsiferous mudstone facies (ML8)

This facies is dominated by mudstone with minor anhydrite (Figure 4C). Core samples show predominantly bedded structures, with relatively planar mudstone beds of stable thickness (typically 0.5–5 cm). Evaporite layers are 0.5–5 cm thick and occur as banded anhydrite interlayers alternating with mud-rich beds. No obvious bioturbation structures are observed.

4.3. Cyclostratigraphic Analysis of Multi-Proxy Records in the Depth Domain

Following a systematic evaluation of various astronomical solutions, Westerhold et al. [82] systematically evaluated different astronomical solutions and concluded that La2010d is the most reliable one for the period since 54 Ma. Accordingly, this study adopts the La2010d astronomical solution as the benchmark for all subsequent astronomical cycle analysis and timescale construction [85].

MTM power-spectrum analysis of the untuned gamma ray record from Well NY1 reveals significant peaks (confidence level > 90%). In Part 1 (Figure 6D), the prominent wavelengths are 34.2, 28.9, 19.3, 12.4, 7.2, 5.1, 3.8, 3.2, 2.8, 2.3, and 1.7–1.4 m. Wavelength peaks exceeding the 95% confidence level indicate an approximate ratio of 20:5:2:1, which matches the theoretical ratios of astronomical cycles and is consistent with Paleogene orbital periodicities [86,87]. These results demonstrate orbital forcing-driven modulation of sedimentation within the Es4cu interval.

COCO analysis of the gamma ray record was performed with 2000 Monte Carlo simulations, testing sedimentation rates from 1 to 30 cm/kyr. The results reveal significant peaks at 5.1 cm/kyr and 8–11.4 cm/kyr. The significance level for the null hypothesis of “no orbital forcing” (H_0) is close to 0.001 (Figure 7C–E), indicating a rather low probability that these optimal sedimentation rates arise in the absence of orbital pacing [78]. Therefore, the most plausible sedimentation rate range is 5.1–11.4 cm/kyr, with a mean of 8.2 cm/kyr. eCOCO analysis of the same record provides more detailed downcore variations in sedimentation rate and allows the studied interval to be divided into three parts: 3370–3420 m yields 4–5.9 cm/kyr, whereas intervals above 3370 m and below 3420 m yield 8.1–11.3 cm/kyr. These estimates are broadly consistent with the COCO results.

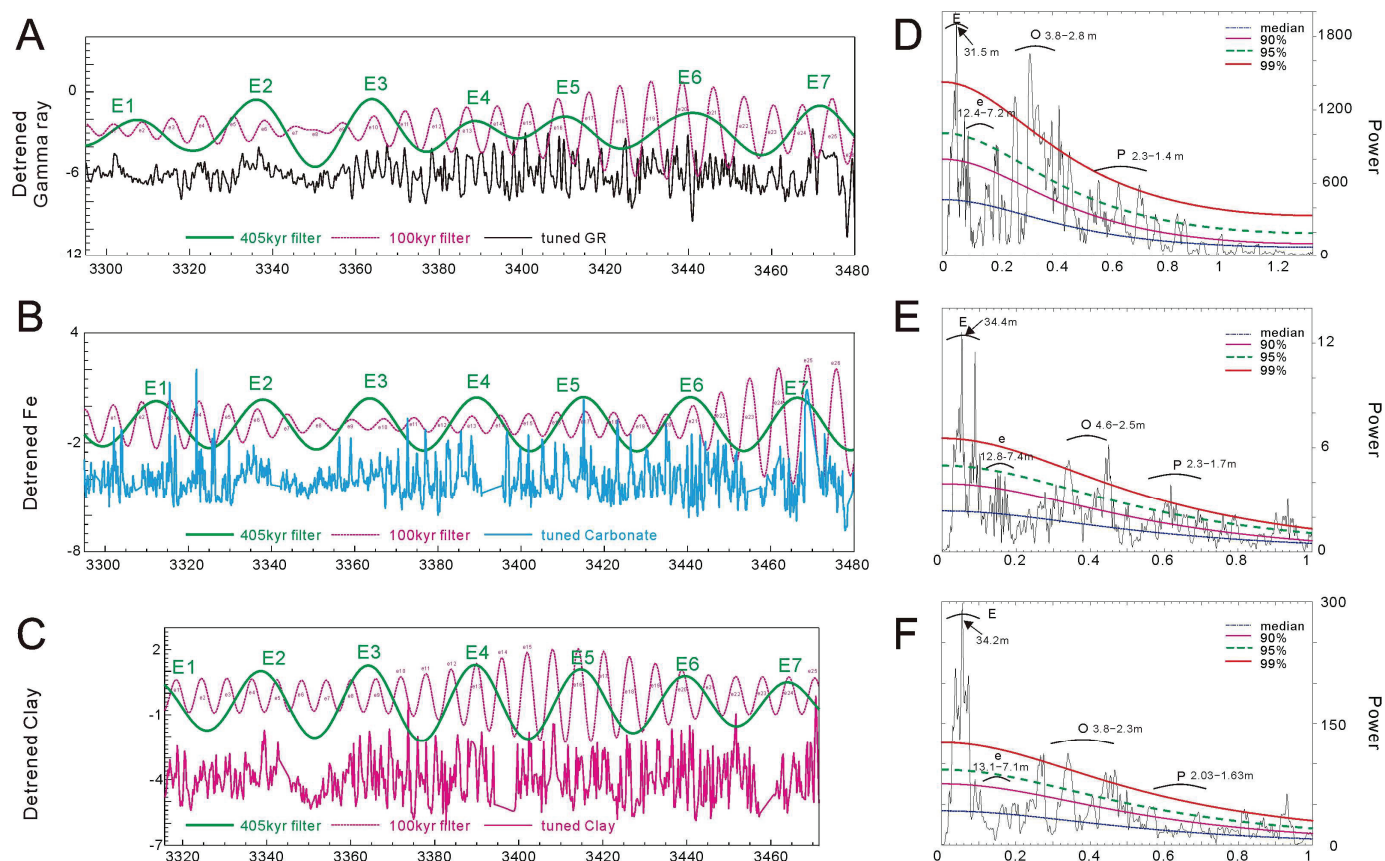


Figure 6. Cyclostratigraphy of the NY1 well. (A–C) Detrended gamma ray, clay, and carbonate series from the upper pure sub-member of the lower fourth member of the Es4cu in the NY1 well were bandpass filtered, respectively. The smoothing window size of the LOESS method was set to 30% of the total thickness of the Es4cu interval in the NY1 well. (D–F) The 2π MTM power spectra of the detrended gamma ray, clay, and carbonate series in (A), (B), and (C), respectively.

Using the sedimentation rates constrained by COCO (Figure 7), the wavelengths identified in the power spectrum were assigned to specific orbital parameters. Specifically, 34.2–28.9 m, 12.4–7.2 m, 3.8–2.8 m, and 2.3–1.4 m corresponding to long eccentricity, short eccentricity, obliquity, and precession, respectively (Figure 7A). Bandpass filtering indicates that the Es4cu interval contains ~7 cycles in the ~29 m band, corresponding to the 405 kyr long eccentricity cycle, labeled E1–E7. Moreover, 26 cycles (coded e1–e26) were identified in the 100 kyr bandpass-filtered GR record, corresponding to 6.3 long eccentricity cycles and 24.5 short eccentricity cycles within the target Es4cu interval. FFT analysis of the processed GR series shows that the 405 kyr eccentricity and 41 kyr obliquity components are the most laterally persistent and stable, whereas other components exhibit more intermittent continuity (Figure 7A,B). Collectively, observations suggest that the 405 kyr long eccentricity and 41 kyr obliquity cycles are the dominant orbital rhythms during deposition of the Es4cu interval.

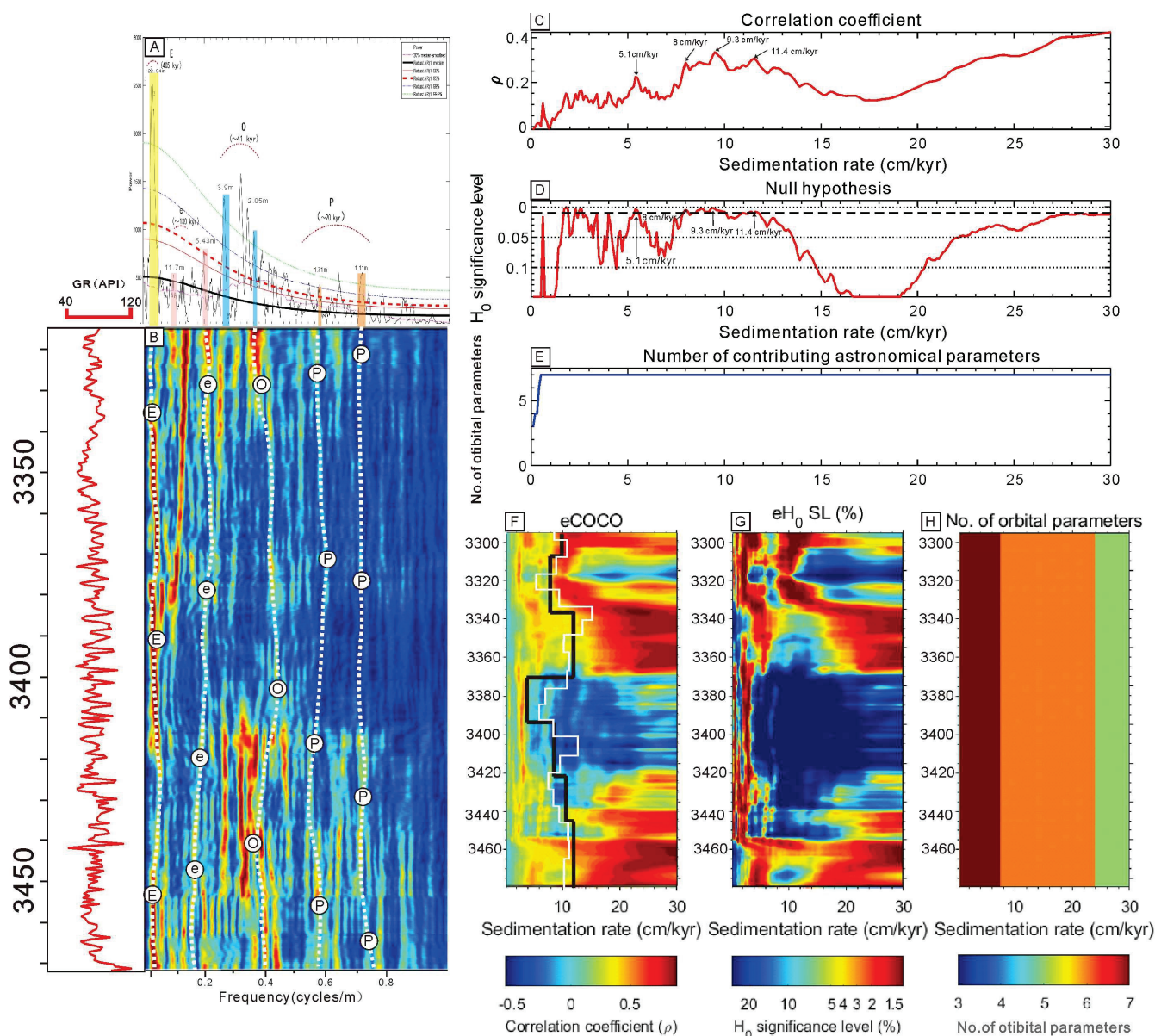


Figure 7. Results of evolutive spectral, COCO, and eCOCO analyses for the gamma ray series of the NY1 well. (A,B) The 2π MTM power spectrum and the evolutive FFT spectrum of the gamma ray (GR) series are shown, with the mean, 90%, 95%, and 99% confidence levels indicated. E, e, O, and P represent the long orbital eccentricity (405 kyr), short orbital eccentricity (~100 kyr), obliquity (~41 kyr), and precession (~19 kyr) cycles, respectively. Our COCO (C–E) and eCOCO (F–H) results display the calculated sedimentation rate variations (black line: based on 405 kyr tuning; white dotted line: based on 100 kyr tuning) from the age model established using the detrended GR series of the NY1 well. The number of Monte Carlo simulations is 5000, with tested sedimentation rates ranging from 1 to 30 cm/kyr in steps of 0.1 cm/kyr. The sliding window size is 50 m with a step of 1.0 m.

GR values are positively correlated with clay content [88,89]. In addition, Fe is a relatively immobile element sensitive to climatic variability. Previous studies have shown that variations in Fe content are significantly correlated with river-borne detrital input [90,91]. Therefore, clay content and Fe were hereby selected as proxy records for mineral-series cyclostratigraphic analysis and compared using the GR-based astronomical model. Both the clay and Fe series exhibit clear cyclicity (Figure 6B,C). Spectral analyses reveal multiple significant peaks (confidence level > 90%), indicating dominant frequency bands consistent with expected orbital-period ratios in both records. Relative to the GR-based model, the

corresponding cycles are largely in-phase, and their bandpass-filtered signals share similar characteristics. A minor mismatch occurs near the trough of cycle E7, where the filtered clay and Fe signals deviate from the filtered GR signal. This discrepancy is primarily attributed to data gaps in the clay and Fe records within this interval. During interpolation, the insertion of numerous low values produces an apparent long eccentricity trough and causes a phase offset of approximately one-quarter of a cycle relative to the GR peak position. Overall, cyclostratigraphic results from both proxy records verify the reliability of the GR-derived orbital framework. To this end, the GR record, which is more continuous and exhibits clearer variability, was used as the primary target series for constructing the astronomical timescale.

4.4. Time-Series Tuning

Herein, a 405 kyr tuning strategy was adopted, considering the 405 kyr cycle as the most stable orbital component in deep time, owing to the strong gravitational influence of Jupiter [86,92–94]. The power-spectrum and evolutive spectral results also support this selection (Figures 6D,E and 7A,B). Based on the ~405 kyr tuning, tuning was additionally performed to another dominant period of ~41 kyr for comparison (Figure 8A,B).

The ~30 m-thick cyclic sequence in the Es4cu member of Well NY1 was subjected to bandpass filtering and tuned to the ~405 kyr long eccentricity cycle, thereby converting the gamma ray data from the depth domain to the time domain. Subsequently, MTM spectral and FFT analyses were performed on the tuned gamma ray data (in the time domain). Significant peaks above the 90% confidence level remain identifiable in these spectra (Figure 8D,E), and their ratios match those expected for orbital periodicities. This confirms successful tuning and validates the previously identified astronomical signals. The resulting astronomical timescale spans ~2.44 Myr. The ~405 kyr bandpass-filtered cycles in the tuned GR series (Figure 8A) are broadly in-phase with the corresponding cycles in La2010d (Figure 8C). While the E1 cycle in the GR time series shows a slight lag relative to La2010d, the strong correlation confirms the tuning model's reliability. Leveraging the ~405 kyr tuning, the 3.8–2.8 m cyclicity was further filtered and tuned to the ~41 kyr obliquity cycle, yielding a timescale of ~2.42 Myr, which is consistent with the long eccentricity tuning result. Based on the analysis in Section 3.2, the astronomical timescale established by Jin et al. was hereby utilized as a fixed anchor point, anchored to the C18r/C19n boundary age from GPTS2020, with the base of the lower Es3x member constrained to an absolute age of 41.28 ± 0.05 Ma. By tying the floating astronomical timescale to this datum, an absolute astronomical timescale was constructed, defining the studied interval of Well NY1 between 41.28 and 43.7 million years (Figure 8B).

The clay and Fe records were tuned using the same procedure and the GR-based astronomical age model (Figure 8B). The results yield astronomical interpretations largely in-phase with the cycles observed in the GR series. Despite minor differences in the durations derived from the three proxy records, they are highly consistent overall, with an uncertainty of approximately ± 0.2 Ma. Collectively, these results validate the proposed multi-proxy approach for generating high-resolution astronomically tuned time series, and cross-proxy comparison boosts the robustness of the chronological framework.

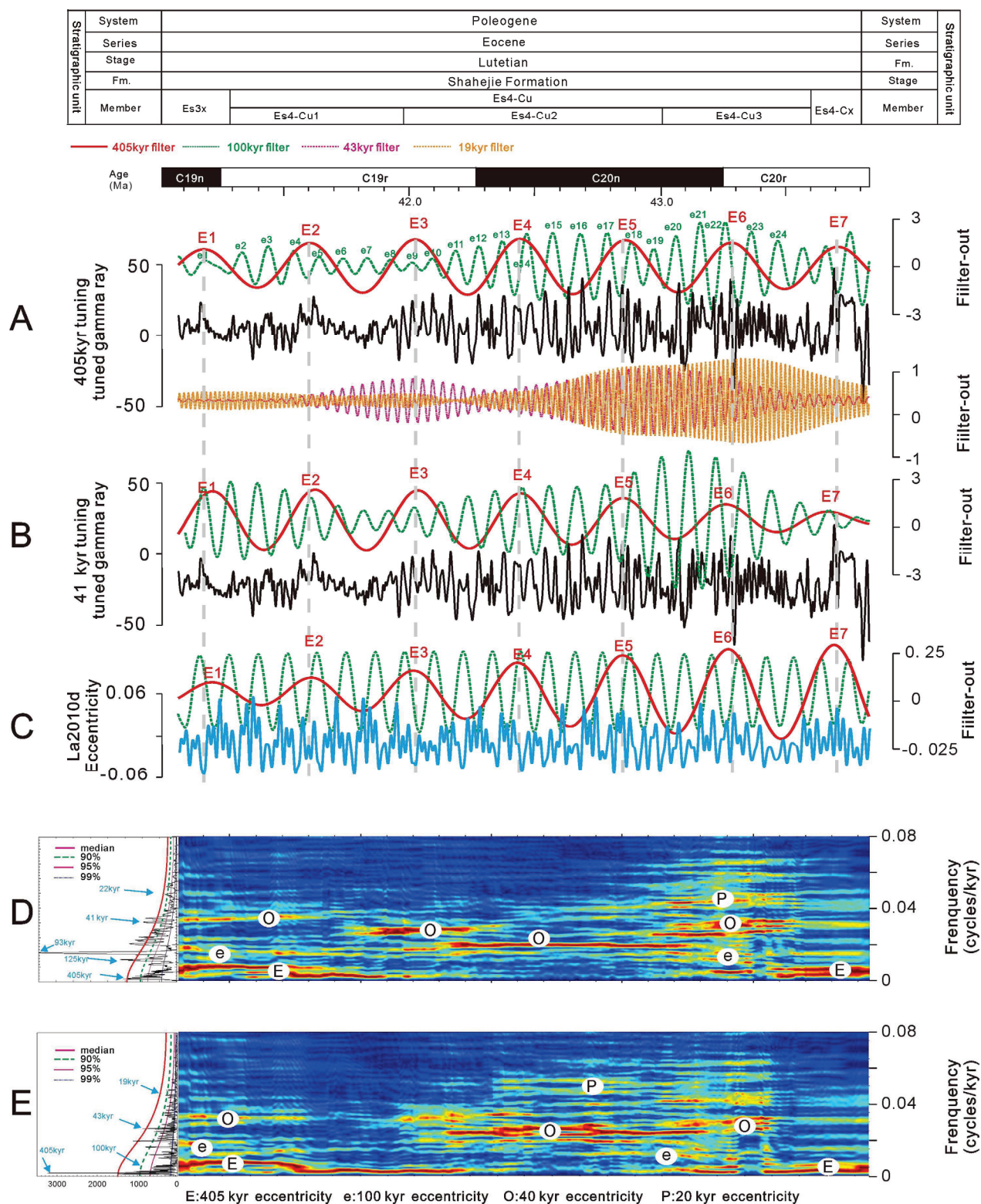


Figure 8. Tuned cyclostratigraphy of the gamma ray and proxy series of the NY1 well in the Dongying Sag. (A) The ~405 kyr cycle-tuned gamma ray series with bandpass-filtered ~405 kyr (red curve), ~100 kyr (green curve), ~41 kyr (pink curve), and ~19 kyr (orange curve) cycles. (B) The ~41 kyr cycle-tuned gamma ray series with bandpass-filtered ~405 kyr (red curve) and ~100 kyr (green curve) cycles. (C) La2010d eccentricity solution filtered for 405 kyr (red curve) and ~100 kyr (green curve) bands. (D,E) The 3π MTM power spectra of the ~405 kyr-tuned and ~41 kyr-tuned gamma ray series, respectively, showing the background $AR(1)$ model and the 90%, 95%, and 99% confidence levels. Evolutionary power spectra (color plots) of the tuned series were computed using a 500 kyr running window.

4.5. Sedimentary Noise Modeling and Paleoclimate Proxy Indicators

A 200 kyr sliding window was used for DYNOT-based sedimentary noise modeling of the tuned GR time series. The DYNOT and ρ_1 results exhibit nearly identical patterns and show markedly higher noise in four intervals within the Es4cu (Figure 10C), reflecting relative variations in lake level through the section. Based on the lake-level curves reported by Du et al. [92] and Miller et al. [95] (Figure 10D), these high noise intervals correspond to relatively low lake-level stages, which can be interpreted as reduced signal-to-noise ratios caused by increased perturbations under shallower-water conditions [79].

Based on high-resolution continuous core scanning and sample analyses from Well NY1, multiple paleoclimate and paleoenvironmental proxy series were hereby obtained and compiled to provide the dataset for subsequent discussion (Section 5.1). The results show broadly coherent downcore patterns among Al, K, Ti, Na, and Fe. Correlation analysis of proxy variables for NY1 (Figure 9a) yields overall correlation coefficients ranging from -0.38 to 0.88 . Sr exhibits a strong positive correlation with Zr ($r = 0.88$, $p < 0.001$), which is also positively correlated with Ca ($r = 0.47$, $p < 0.001$) and U ($r = 0.38$, $p < 0.001$), suggesting broadly similar geochemical behavior and/or shared controls related to source input and mineral composition. In contrast, Ca is negatively correlated with Ti and Al, with the Ca–Ti relationship being significant ($r = -0.38$, $p < 0.001$). Notably, in fine-grained lacustrine strata, Al is preferentially hosted by clay minerals [96]. Accordingly, Al and Ti are taken as proxies for terrigenous weathering products delivered to the lake via fluvial transport and episodic events during deposition, whereas Sr and Ca in lacustrine sediments are more likely of authigenic origin. Ba shows generally weak correlations with other elements, indicating relatively independent environmental behavior. Correlation results for the three cyclostratigraphic proxy groups further confirm positive GR–U correlation alone, with the Fe–U relationship being insignificant. The clay mineral series shows a weak yet significant correlation with Ca and only a very minimal correlation with Al. These patterns imply that the three proxy groups are largely independent for cyclostratigraphic analysis, supporting the selection of the proxies used in this study.

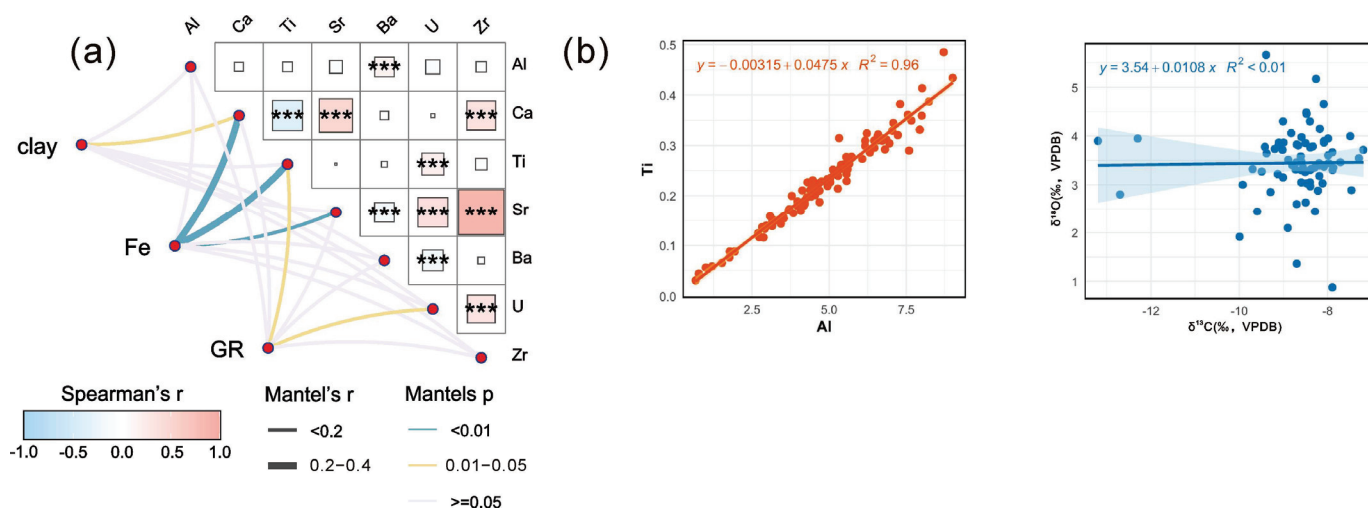


Figure 9. Correlation analysis of proxy indicators. (a) Correlation matrix between paleoclimate proxies (major and trace elements) and cyclostratigraphic proxies (GR, Fe, and the clay mineral series) for shale in the upper Es4 Member (Es4cu). (b) Cross-plots of Al versus Ti and $\delta^{18}O$ versus $\delta^{13}C$ for rock samples from the Dongying Depression, both showing strong correlations. *** indicate the significance level at $p < 0.001$.

The Sr/Ba ratio is extensively considered as an effective proxy for salinity in sedimentary systems [97,98], and previous studies have demonstrated its reproducibility and

regional applicability for paleosalinity reconstructions in the Dongying Depression. In addition, redox-sensitive trace elements commonly show pronounced enrichment under reducing conditions; uranium (U) enrichment therefore provides an independent constraint on redox state [99]. Paleo-redox conditions are typically evaluated using element ratios normalized to Al to correct for dilution by detrital inputs [99]. Based on these observations, we selected proxies that reflect paleoweathering intensity, including the chemical index of weathering (CIW) [96,100], together with indicators of paleo-redox conditions U/Al [101], paleosalinity Sr/Ba [10,21,102], paleoproductivity Ca/Al [60], and provenance/terrigenous input (Al). In addition, carbonate stable isotopes ($\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$) were used to provide independent constraints on internal lake processes. $\delta^{18}\text{O}_{\text{carb}}$ is primarily controlled by the isotopic composition of lake water and temperature, and is thus sensitive to hydrological changes (evaporation vs. precipitation) [103–106]. $\delta^{13}\text{C}_{\text{carb}}$ mainly reflects the composition of the dissolved inorganic carbon pool and is influenced by multiple processes, including primary productivity, organic matter degradation, and water-column stratification [107–109]. Despite the extensively documented response mechanisms of these proxies to environmental variations in the lacustrine setting of the Bohai Bay Basin, the potential influences of diagenesis and provenance should still be evaluated before applying them to constrain orbital-scale climate cycles (Figure 9b,c) [110]. First, the strong correlation between Al and Ti suggests stable provenance during deposition of the studied shale succession. Second, burial-history reconstructions for the Dongying Depression indicate that strata deposited during the Es4 and Es3 intervals mainly experienced progressive subsidence [111], implying that they were not subjected to intense late-stage diagenetic overprinting. Ma et al. [111] compared $\delta^{18}\text{O}_{\text{carb}}$ values between micritic and sparry carbonates from Well NY1 and conducted dolomite diagenetic analyses, concluding that carbonate deposition in the Es4 Member of the Shahejie Formation underwent only minimal diagenetic modification. In the present study, $\delta^{18}\text{O}_{\text{carb}}$ also shows a strong correlation with $\delta^{13}\text{C}_{\text{carb}}$, further supporting limited diagenetic alteration. In addition, cross-validation among proxies was performed (e.g., integrating TOC, productivity indicators, and redox proxies). Intervals affected by late-stage calcite veining were excluded, and coupled analyses of productivity, water-column stratification, and anoxia reveal coherent covariation among the proxies (Figure 10B), indicating a robust response to environmental change.

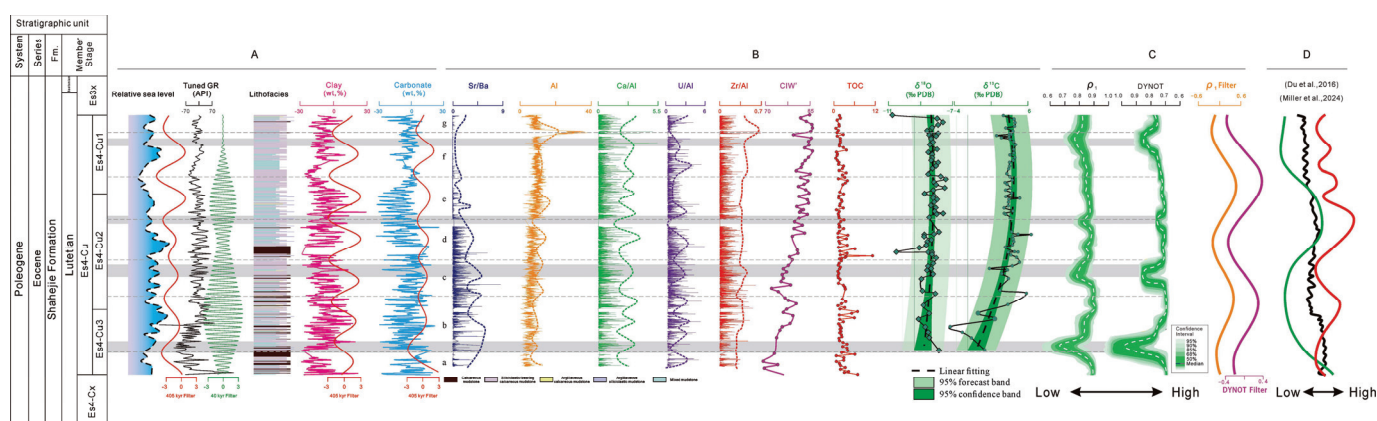


Figure 10. Tuned cyclostratigraphy with paleoclimate proxies and sedimentary noise-derived lake-level analysis for the NY1 well in the Dongying Sag. **(A)** Tuned gamma ray, clay, and carbonate time series with bandpass filtered 405 kyr and 41 kyr cycles. The vertical evolution of lithofacies is established based on carbonate mineral content, clay mineral content (wt.%), and proxy series. **(B)** Paleoclimate proxies showing Al content (wt.%), Ca/Al, U/Al, Zr/Al, and Sr/Ba ratios, carbonate $\delta^{18}\text{O}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{carb}}$ values (‰, VPDB), weathering indices, and total organic carbon (TOC) trends. **(C)** DYNOT and ρ_1 models of the tuned GR curve. The DYNOT model uses a Monte Carlo simulation window of 100–200 kyr with a step of 5 kyr; the ρ_1 model uses a 100–200 kyr window. **(D)** Global sea-level modified from [92,95].

The Zr/Al ratio ranges from 0.01 to 0.66, whereas Sr/Ba varies from 0.7 to 12.2. Higher-frequency fluctuations occur in the lower part of the Es4cu interval and near the Es4cu–Es3L boundary (Figure 10B). CIW values range from 63 to 84. Carbonate isotopic compositions span -3.6‰ to 5.7‰ for $\delta^{13}\text{C}_{\text{carb}}$ and -10.1‰ to -7.2‰ for $\delta^{18}\text{O}_{\text{carb}}$, respectively. These isotope values are consistent with those reported for mudstone samples from other Shahejie Formation cores in the Bohai Bay Basin [112].

5. Discussion

5.1. Climatic Significance of the Multi-Proxy Records and Their Responses to Orbital Forcing

Based on the high-resolution floating astronomical timescale, an integrated analysis incorporating the vertical lithofacies' succession, multiple paleoclimate proxy records, and sedimentary noise models was conducted to assess coherent orbital-scale forcing responses of the depositional system in the upper sub-member of Es4cu. Within the Es4cu interval, the lithofacies' succession features frequent alternations in a rhythmic “calcareous mudstone–mixed mudstone–mudstone” motif [113], a pattern consistent with recent interpretations and attributed to orbital-scale climatic and hydrological fluctuations.

In Dataset Group A, the GR record shows a high signal-to-noise ratio among the paleoclimate proxies and is only weakly affected by diagenesis [114,115]. High GR values generally indicate enrichment of clay and organic matter driven by enhanced chemical weathering under warm and humid conditions [116,117]. In contrast, low GR values correspond to more arid or cold-dry conditions, when carbonates and gypsum become more abundant. GR variations are primarily controlled by mud content (enriched in radioactive elements), whereas evaporites and relatively pure carbonates yield low GR values. Accordingly, the GR trend is similar to the clay-content record but opposite to the carbonate-content record. Bandpass filtering of these three hydroclimate-sensitive datasets reveals two shifts in the dominant periodicity during deposition of the Es4cu interval. These occur broadly between the trough of cycle E1 and the trough of E3, between the trough of E3 and the peak of E6, and from the peak of E6 to E7. In the lithofacies' succession, these intervals correspond to a transition from calcareous mudstone-dominated facies to felsic-rich calcareous mudstone dominance, followed by a mixed-mudstone-dominated interval (Figure 10A). Organic-rich laminated calcareous mudstone facies (e.g., ML1 and ML3) commonly coincide with GR maxima, accompanied by higher clay contents and lower carbonate contents. This proxy facies association indicates abundant fine-grained terrigenous input under strong chemical weathering, elevated lacustrine productivity, and oxygen-depleted bottom waters. Together, these features point to a warm, humid climate and relatively high lake level [118]. In contrast, carbonate-rich facies (e.g., ML4) and organic-lean bedded mudstone facies (ML6) occur during GR minima, characterized by a marked decrease in clay content and a corresponding increase in carbonate content. This mineralogical shift reflects reduced terrigenous supply and stronger evaporative control on lake water chemistry, consistent with lake level lowering under arid conditions and potential salinification [119]. Comparison with the obliquity band further reveals that obliquity maxima generally coincide with shale deposition and high GR values, indicating warm and humid conditions. Obliquity minima typically correspond to low GR calcareous mudstone and argillaceous limestone deposited under colder and drier conditions; the lowest GR values near the base additionally mark intervals with gypsiferous mudstone.

Group B integrates multiple proxies (CIW, Al, Zr/Al, U/Al, Sr/Ba, and Ca/Al) to further refine the inferred wet–dry cyclicity and uses coeval $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ records to independently validate the reconstructed climate cycles (Figure 10B). For equilibrium carbonates precipitated in lacustrine settings, previous studies have suggested an isotopic decrease of $\sim 0.24\text{‰}$ per 1 °C increase in temperature [109]. Applying this relationship to

the isotopic amplitudes reported here implies temperature differences exceeding 15 °C, which is inconsistent with contemporaneous climate estimates derived from foraminiferal isotopes [77]. Temperature is therefore unlikely to be the dominant control; instead, the precipitation/evaporation (P/E) balance and water-source variability are interpreted as the primary drivers of isotopic change. The periodic wet–dry variations reconstructed from Group A proxies indicate recurrent episodes of enhanced evaporation in the paleo-Dongying Lake. The strong covariation between isotopic compositions and dolomite reported for wells NY1 and L69 by Ma et al. [111] supports the interpretation that authigenic carbonates in the basin were modulated by evaporation. Most samples in this study likewise show a strong positive correlation between carbon and oxygen isotopes. A plausible mechanism is that evaporation increases lake water alkalinity and promotes preferential loss of the lighter oxygen isotope (^{16}O), thereby enriching carbonates in ^{18}O . Meanwhile, $\delta^{13}\text{C}_{\text{carb}}$ tends to increase as elevated nutrient availability enhances surface water productivity. In contrast, intervals characterized by high $\delta^{18}\text{O}_{\text{carb}}$ but low $\delta^{13}\text{C}_{\text{carb}}$ are interpreted to reflect oxidation of organic matter in a shallow-lake setting, where lower total dissolved inorganic carbon contents drive lower $\delta^{13}\text{C}$ values [109].

On the basis of Milankovitch-scale cyclicity, the climate evolution was further subdivided into Stages a, b, c, d, f, and g. The dry endmember, commonly associated with carbonate-rich facies (ML4) or organic-lean bedded mudstone (ML6), is characterized by low CIW values (dominant physical weathering), elevated Sr/Ba and Ca/Al ratios (higher salinity due to evaporative concentration and enhanced authigenic carbonate precipitation), positive shifts in $\delta^{18}\text{O}_{\text{carb}}$ (strong evaporation), and decreased U/Al ratios. In contrast, represented by organic-rich laminated calcareous mudstone facies (ML1–ML3) and mixed mudstone (ML2), the humid endmember shows high CIW values (>75, indicating intense chemical weathering), relatively low Sr/Ba (<0.2) and Ca/Al ratios (lower salinity and dilution by terrigenous input), increased U/Al ratios (anoxic bottom waters), and negative shifts in $\delta^{18}\text{O}_{\text{carb}}$ (dilution by freshwater input). Downcore variations in these proxies are consistent with the eccentricity and obliquity signals inferred from the GR record. Combined proxy facies relationships indicate that the basal Es4cu interval was initially in a dry state at the a–b peak. It then evolved toward progressively more humid conditions (b–e) with superimposed dry–wet oscillations. This transition is marked by synchronous decreases in salinity proxies and Ca/Al, opposite to increasing CIW and Al, suggesting gradually enhanced precipitation and continental weathering. This interpretation is further supported by a coeval negative shift in $\delta^{18}\text{O}_{\text{carb}}$. In the final stage, proxy records indicate a return toward drier conditions (late e to f). However, CIW values remain at moderate levels, implying that overall weathering intensity remains elevated relative to that of the initial dry phase. Notably, Zr/Al commonly shows peaks near cycle transition surfaces (Figure 10B), which may reflect pulsed detrital inputs associated with enhanced seasonal rainfall or short-lived flood events during shifts from dry to humid conditions [120].

Comparisons among individual depositional cycles further support this interpretation. For instance, relative to Stage b, Stage c shows lower mean carbonate content (25.057 wt.%) and Sr/Ba (0.36) (Figure 10B). In contrast, Stage c exhibits higher mean GR values (86.28 API), elevated felsic-mineral content (32.302 wt.%), higher U/Al, higher CIW (68.496), and higher Al (mean 4.301). Together, these changes indicate a pronounced decrease in water salinity, persistently humid conditions, and continued increases in sediment supply. They also imply that high eccentricity conditions amplify monsoon precipitation variability, fostering a wetter climatic background and elevated lake levels during Stage c. In both stages, $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ are predominantly anti-phased, with only localized intervals exhibiting in-phase behavior. This points to warm, humid conditions prevailing in East Asia during eccentricity maxima, which coincide with prominent negative $\delta^{13}\text{C}_{\text{carb}}$

excursions [121,122]. The negative $\delta^{13}\text{C}_{\text{carb}}$ shift is interpreted to reflect rapid release of isotopically light carbon during warm periods [123]. In-phase intervals may reflect superposition of other orbital components, leading to phase offsets between precipitation seasonality and temperature, and thus partially decoupling the isotope responses [124]. Eccentricity-scale fluctuations in TOC, carbon–oxygen isotopes, and salinity proxies indicate that biogeochemical evolution in this marginal sea–proximal system was strongly governed by astronomical forcing. During humid intervals (i.e., strengthened monsoon conditions), increased precipitation raised the lake level, and freshwater input reduced salinity. However, a higher lake level likely increased the probability of (1) episodic connection with the open ocean and/or (2) seawater-modulated groundwater seepage across barriers, thereby enhancing potential marine influence; consequently, elevated salinity values may also occur within some humid phases. In contrast, during arid intervals (weakened monsoon conditions), reduced rainfall and lower lake levels diminished the linkage to the open ocean. Under such climatically driven extremes, evaporation became the primary control on lake water chemistry, whereas marine influence played a subordinate role.

From an orbital paleoclimate perspective, the astronomical framework allows the fine-grained deposits in the lower part of the Es4cu interval in Well NY1 to be subdivided into seven ~405 kyr cycles and 26~100 kyr cycles (Figure 10). The number of cycles and the positions of their boundaries are broadly consistent with the climate cycles identified from the multi-proxy records, providing additional support for the robustness of the Milankovitch interpretation. In other words, from long eccentricity cycle E7 to E1, basin hydroclimate progressively shifted toward more humid conditions. This transition is associated with enhanced mechanical sedimentation, increased sediment supply, higher seasonal productivity, and systematic lithological changes. The coupled responses of the two proxy groups further indicate that long eccentricity and obliquity exerted strong forcing on the hydroclimate during this interval. Most proxies suggest warmer and more humid conditions during obliquity maxima. Therefore, obliquity forcing likely acted as the primary modulator of climate hydrological variability throughout the Es4cu interval.

5.2. Lake-Level Responses in the Dongying Area

Sedimentary noise in the records may reflect both water-depth-related disturbances (e.g., storms, tides, bioturbation, and unstable sedimentation rates) and water-depth-independent noise (e.g., age-model errors, tectonism, and volcanism) [78]. The bandpass-filtered time series from the three proxy groups display in-phase cyclic variations, and the DYNOT and ρ_1 outputs derived from the tuned GR series show nearly identical patterns (Figure 10C). This agreement indicates that chronological uncertainty had a minor influence on the noise estimates. Seismically induced deformation can trigger hydrological changes and generate additional sedimentary noise. In Well NY1, a small number of syndepositional deformation structures were observed near the base and middle parts of the Es4u unit (Figure 4I), suggesting that the Dongying Sag may have been affected by seismic activity around ~43.63 Ma and ~42.5 Ma [33]. Sedimentary noise shows a corresponding increase during these intervals (Figure 10C). In the remaining parts of the section, no comparable evidence is observed, supporting the applicability of sedimentary noise modeling for reconstructing lake-level changes in the Dongying area [33].

Low sedimentary noise levels correspond to high lake levels, whereas high noise values indicate low lake levels. Intervals of low sedimentary noise typically coincide with dark-gray, organic-rich laminated mixed facies or calcareous mudstone assemblages (ML1 and ML2). These facies are characterized by low carbonate content, high clay content, high GR value, low Sr/Ba, low Al, and relatively high U/Al (Figure 10B), indicating a high lake level under humid climate conditions. In contrast, high noise intervals mainly

correspond to a facies assemblage dominated by light-gray bedded calcareous mudstone with thin calcite veins (ML6). This assemblage shows high carbonate content, low clay content, and low GR values, and it is associated with pollen taxa indicative of arid and cold conditions (e.g., Ephedripites and Labitricolpites) [125]. Therefore, the relationships among our reconstructed lake-level variations, lithofacies changes, and carbonate and clay contents can be explained by chemical weathering driven by land-sea hydroclimatic variability. Together, these features indicate a shallow-lake environment under an arid climate. As discussed in Section 5.1, from the lower part of the Es4cu interval to the top boundary of the lower sub-member of Member 3, the overall hydroclimate trend transitions from arid to humid conditions, and it can be further divided into four major stages: arid, semi-humid, humid, and humid to semi-humid. The sedimentary noise record similarly indicates a rapid rise in lake level from the base of Es4cu, followed by a sustained highstand with six minor lake-level oscillations. These short-term fluctuations may reflect increased regional rainfall input under a monsoonal regime, which enhanced depositional perturbations. Toward the top of the lower Member 3, lake level declines again, which is consistent with trends inferred from the proxy records. Moreover, bandpass filtering of the interpreted noise model reveals a ~1.2 Myr modulated long-period cycle (Figure 10C). On this basis, Es4cu can be subdivided into three lake-level phases: rapid lake expansion, early highstand, and late highstand, which are consistent with the scheme of [95] (Figure 10D). The episodic discontinuities in the eCOCO results (Figure 10C,D) further support markedly increased depositional instability during lake-level lowstands. This behavior is clearly linked to relatively arid climatic backgrounds. Collectively, these lines of evidence indicate that, under monsoon-driven wet-dry cyclicity, variations in chemical weathering intensity dynamically regulated lake level and terrigenous sediment flux to the basin [114,116].

5.3. Orbital Forcing and Hydroclimate Dynamics

The lithofacies succession and multi-proxy records established in this study indicate that, during deposition of the Es4cu interval, the study area experienced repeated oscillations between arid/semi-arid and relatively humid conditions. This supports previous conclusions that the Asian monsoon system began to exert a periodic influence on central eastern China by the middle Eocene [34,52,65]. Potential moisture sources include southerly moisture transport associated with the Indian and Pacific summer monsoons, as well as westerly delivery that may have originated from the Proto-Tethys region [45]. Notably, the PETM triggered a short-lived humid phase in central eastern China [126,127], and extreme global warming likely promoted inland expansion of monsoonal rainfall. In addition, the broad arid belt in central China was largely controlled by the subtropical high-pressure system, which exhibited pronounced wet-dry oscillations during the late Eocene. Sedimentological evidence from the Jiangnan Basin and periodic vegetation “greening” in central China indicate orbital-scale hydroclimate oscillations [128]. These have been attributed to orbitally driven changes in summer monsoon intensity [129] and are further supported by climate model simulations [38]. Together, these results suggest that orbitally paced monsoon incursions, with transient perturbations during extreme warming events such as the PETM, disrupted an otherwise persistent arid to semi-arid background climate [40,126]. Consistent with this framework, MTM power spectra of the ~405 kyr-tuned GR, clay, and Fe time series show significant peaks at the ~405 kyr long eccentricity band, ~123–95 kyr short eccentricity band, ~43–41 kyr obliquity band, and ~22–19 kyr precession band. This pattern indicates a strong linkage between quasi-periodic proxy variability and orbitally forced insolation changes. Therefore, the quasi-cyclic fluctuations in these proxies are interpreted as alternating wet-dry cycles, driven by orbitally induced insolation variability and

expressed through changes in monsoon strength under Hadley cell dynamics associated with the subtropical high-pressure system.

In addition, the sedimentary noise model reveals a prominent ~1.2 Myr cycle in the $\rho 1$ series and DYNOT series. This agrees with results from the same stratigraphic level in other wells in the study area reported by Ma [33], Zhang [27], and Zhong [130]. In addition, the amplitude variations in the ~1.2 Myr curve show a similar trend to those of the filtered curves for the three proxy records. This pattern suggests that the long-obliquity cycle may, to some extent, modulate the eccentricity cycle. Specifically, intervals with high amplitudes in the ~1.2 Myr bandpass-filtered curve coincide with strong-amplitude eccentricity variability and exhibit consistent responses in the paleoclimate proxies. During these high-amplitude intervals, the proxies indicate relatively warm and humid conditions, higher lake level, and more reducing bottom-water conditions (e.g., low noise, high clay content, elevated U/Al, and high CIW). In contrast, low-amplitude intervals are more commonly associated with cold-dry conditions, reflected by increased carbonate contents and reduced clay, Al, and CIW values. Accordingly, the forcing mechanism across kyr-Myr timescales can be interpreted as follows: the ~1.2 Myr obliquity cycle influences the meridional insolation gradient by altering the poleward transport of heat and water vapor from low to high latitudes. At the peak amplitude of this ~1.2 Myr cycle, eccentricity variability is correspondingly amplified. Enhanced forcing during these intervals may increase the cross-hemispheric pressure contrast between continental low-pressure centers and subtropical highs, promoting a northward displacement of the ITCZ, which likely dominated the climate system over southern China at that time [130–132]. This shift coincides with a coherent migration of the paleo-Hadley circulation, which heightens climatic seasonality—characterized by hotter, wetter summers and colder, drier winters—while raising overall mean precipitation levels. The resulting hydroclimatic responses may include lake-level rise, intensified chemical weathering, and increased sediment supply to the basin.

Growing evidence supports a strong obliquity control on the middle-late Eocene climate [133]. As shown in Section 5.1, intervals with high amplitude in the obliquity band-filtered curve are characterized by lithofacies and proxy records that jointly indicate abundant terrigenous input, sufficient nutrient supply, and high productivity in the lake system. One hypothesis proposes that obliquity forcing on regional hydroclimate may be mediated by ice-sheet feedbacks. Although the Antarctic ice sheet had not expanded widely in the middle Eocene, recent studies suggest that tidewater glaciers may have existed in the middle Eocene, implying a substantial ice volume before the Eocene-Oligocene transition [134,135]. Whether such early ice could influence climate by modifying sea levels and land–sea thermal contrasts remains unconfirmed. However, the dominant periodicity shift identified here at ~41.5–42 Ma (Figure 8D,E) broadly coincides with global cooling and a brief occurrence of high-latitude Northern Hemisphere glaciation [136]. This temporal correspondence suggests that in the Bohai Bay Basin, an obliquity-forced ice-sheet feedback mechanism may have been operative. A second hypothesis emphasizes that obliquity primarily affects high-latitude insolation. By changing the extent of polar night and the meridional contrast in insolation within and between hemispheres, obliquity can alter equator-to-pole and cross-equatorial insolation gradients. This may modulate hydroclimate by influencing the Hadley cell width and the transport of moisture and heat. Within this framework, the ~1.2 Myr obliquity cycle exerts influences on low latitudes through adjustments to the meridional insolation gradient, providing a plausible explanation for the pronounced ~1.2 Myr signal in the proposed clay record and sediment noise models. This mechanism further explains the strong obliquity imprint observed in numerous low-to-mid latitude paleoclimate records. Multi-proxy interpretations indicate

that obliquity most likely modulates regional climatic conditions primarily by regulating the intensity of the East Asian summer monsoon [137–140]. During obliquity maxima (minima), stronger (weaker) land heating relative to the ocean may have generated a stronger (weaker) monsoon and associated precipitation, leading to wetter (drier) conditions [141]. This would increase continental runoff and fluvial sediment supply, which is consistent with our records (Figure 10). A pronounced obliquity-paced signal and associated switches in dominant orbital forcing have also been reported from coeval sedimentary archives across China (e.g., the Xining, Subei, Weihe, Jiangnan, Nanxiang, and Beibuwan basins) [33,133,142–144]. These observations argue against the view that obliquity acted solely through the modulation of high-latitude insolation. Instead, during the mid–late Eocene cooling interval, obliquity likely played an important role in shaping hydroclimate evolution across East Asia. The shift in dominant orbital periodicity recorded in sediments may also have been influenced by the uplift of the Tibetan Plateau. Around ~42 Ma, significant deceleration and rotation of the northward-moving Indian plate have been linked to a pulse-like uplift of the central Tibetan Plateau (e.g., the Tanggula Mountains) [140]. The resulting topographic barrier could have effectively restricted south-derived moisture transport into central China and farther into the continental interior. Enhanced land–sea thermal contrast, together with a strengthened cross-equatorial pressure gradient for monsoonal precipitation (topographic–thermal forcing), would have promoted expansion of the East Asian monsoon (EAM) system and potentially altered the expression of orbital forcing. One plausible mechanism is that plateau uplift weakened teleconnections between low- and mid-latitude Asia, rendering the regional climate system more sensitive.

In our records, a clear 405-kyr cycle is detected, whereas the ~100-kyr band is not prominent, differing from the strong ~100-kyr modulation reported from the Jiangnan and Xining basins. Several explanations are proposed. (1) Differential sedimentary responses to orbital forcing. Unlike the Es4cu interval, where gypsum–halite layers are only sporadically observed near the base, cyclostratigraphic–spectral analysis of the Qianjiang Formation shows that rhythmically developed saline-lake deposits and intersalt mudstones, as well as shallow-water clastic mudstones, are preferentially paced by ~40 kyr and ~100 kyr cycles, respectively [65]. Similarly, in the Xining Basin, superposed obliquity and short-eccentricity signals have been identified in mudstone–gypsum successions, implying that salinity thresholds during deposition can amplify the obliquity signal, whereas under contrasting conditions, the intersalt mudstones preferentially preserve eccentricity-scale variability. (2) Compared with the marginal sea-influenced setting considered here, the Qianjiang paleo-lake was more closed and evaporation-dominated. In contrast, the Dongying Depression likely experienced stronger potential marine influence and additional modulation by an ice-sheet-related ~1.2 Myr cycle, which may have obscured shorter eccentricity and precession signals [145]. (3) Nonlinear responses of the climate system and/or nonlinear distortions in the stratigraphic record may have transformed higher-frequency orbital forcing, transferring variance from short-period bands (short eccentricity and precession) into the long eccentricity band.

Notably, even when a strong obliquity signal is present, some intervals show relatively low carbonate contents but higher felsic and clay mineral abundances, accompanied by low CIW, low Al, and low U/Al. This pattern suggests that sedimentation was influenced by the superposition of other orbital components rather than by obliquity alone. Proxy behavior indicates that intervals of high eccentricity combined with high obliquity are characterized by higher clay contents, higher CIW, and elevated Zr/Al, consistent with a strengthened monsoon circulation (Figure 10B). In contrast, during high eccentricity but low obliquity, the cross-equatorial pressure gradient would be weaker than under high eccentricity–high obliquity conditions, resulting in reduced monsoonal precipitation. During low eccentricity but high obliquity, both the northward displacement of the ITCZ and the cross-equatorial insolation

gradient would also be weaker than in the high eccentricity–high obliquity case. This would favor relatively higher carbonate contents and lower felsic and clay mineral contents [146]. These relationships indicate that fine-grained lacustrine deposits in the study area were jointly influenced by eccentricity, obliquity, and precession, reflecting combined control by multiple orbital cycles. Crucially, periodic insolation changes driven by different orbital components can generate nonlinear amplitude modulation and combination frequencies (Figure 11), thereby exciting distinct climate rhythms [147]. This may produce phase offsets between summer warmth (thermal forcing) and the rainy season (precipitation forcing). For example, the onset of the rainy season may not coincide with the beginning of summer and can start in mid-to-late summer. Such phase offsets, together with orbitally driven interannual variability in the duration of summer and the rainy season [124], likely determined which climate mode dominated in a given year. These dynamics are ultimately recorded in the vertical lithofacies succession and in the multi-proxy datasets.

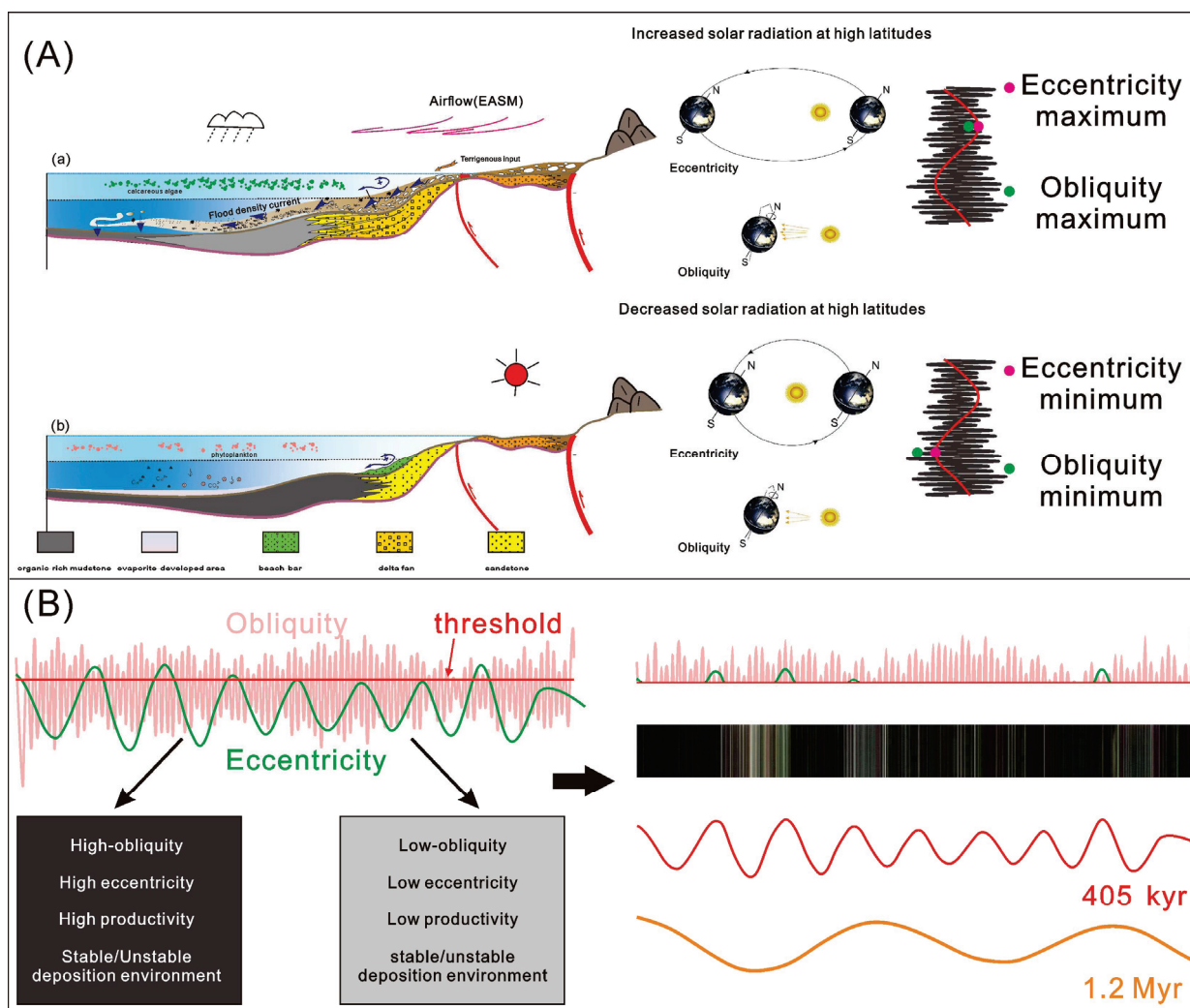


Figure 11. Sedimentary models driven by astronomical forcing. (A) Depositional patterns controlled by Earth's orbital configurations. The right panel shows Earth's orbital eccentricity, obliquity, and precession curves; the left panel illustrates the corresponding depositional patterns: (a) maximum eccentricity and high obliquity, leading to strong monsoon and high terrestrial input; and (b) low eccentricity and low obliquity, resulting in weak monsoon and reduced terrestrial input. (B) Simplified sedimentary process model of nonlinear climate feedback linked to ~405 kyr and ~1.2 Myr eccentricity and obliquity cycles in mid-latitudes. When the influence of different orbital forcings on surface climate exceeds a critical threshold (internal feedback) within a depositional system, distinct imprints can be recorded in the sedimentary sequences, modified from [142].

5.4. Implications of Orbital Forcing for Predicting Shale-Oil Sweet Spots

Aforementioned findings demonstrate that astronomically forced hydroclimate variability exerts a pronounced control on terrigenous input, paleoproductivity, and redox conditions [148]. Eccentricity and obliquity—the dominant orbital parameters—regulate the intensity and seasonality of the East Asian monsoon, thereby exerting dual control on organic matter enrichment in the lake basin via both productivity and preservation processes. These controls are consistently recorded by the integrated paleoclimate and paleoenvironment proxies used in this study. Between ~41.6 and ~43.15 Ma, climate conditions are overall relatively humid. When eccentricity and obliquity reach coupled maxima, clay minerals (e.g., illite and kaolinite) and associated terrigenous elements (e.g., Al and Si), together with GR, increase to peak values (Figures 8D,E and 10A). This indicates intensified chemical weathering and enhanced delivery of terrigenous nutrients (e.g., Si and Fe) to the lake, which likely stimulates primary productivity in surface waters and provides a material basis for organic matter accumulation [63,149]. TOC also increases during this interval. Elevated surface water productivity promotes organic matter production; subsequent degradation of sinking organic matter consumes dissolved oxygen, lowering oxygen levels in the water column. In a stratified lake, this process promotes bottom-water anoxia, consistent with the coeval behavior of U/Al (Figure 10B), and thus enhances organic matter preservation. In contrast, during eccentricity and obliquity minima, reduced rainfall likely decreases catchment vegetation cover. Under such conditions, terrigenous detritus could be supplied more persistently, promoting better oxygenation of the water column. Concurrently, weakened surface water productivity and stronger detrital dilution further reduce organic matter contents. However, during the climate-transition intervals before ~43.15 Ma or around ~41.6 Ma, orbital minima under a relatively arid background may be accompanied by reduced seasonality and smaller environmental variability [150]. More quiescent water-column conditions could favor the development of bottom-water anoxia, which would also be conducive to organic matter enrichment [151–154].

Orbital cyclicity not only controls the stratigraphic distribution of organic-rich intervals but also drives the heterogeneity of sedimentary microfacies and rock fabric through climate hydrological forcing. In the current exploration and development of shale oil in the Bohai Bay Basin, the lamination characteristics of distinct lithofacies assemblages are widely acknowledged to exert a profound influence on the hydrocarbon generation potential and reservoir capacity of shale oil reservoirs [155,156]. Clay mineral-rich laminae are commonly associated with higher organic matter contents and thus provide the material basis for hydrocarbon generation. In contrast, brittle mineral laminae, such as cryptocrystalline or micritic calcite layers [157], tend to host better-developed pore space and represent key reservoirs for free oil [158–160]. Therefore, sedimentary processes paced by astronomical cycles directly imprint the critical geological attributes of shale oil sweet spots [161]. Our results suggest that coupled precession and obliquity forcing generated meter-scale, high-frequency mudstone marl lithofacies cycles in the Dongying Sag [162]. Under favorable orbital phases, organic-rich laminated shales not only exhibit high-organic-matter abundance, but their distinctive lamination also confers higher brittleness and more developed micro- to nanopore systems [156,163]. As a result, these intervals combine strong hydrocarbon generation potential with favorable fracability. The integrated lithofacies and proxy datasets compiled here support this interpretation. We further propose and validate a workflow that uses GR logs to reconstruct paleoclimate curves, demonstrating its rationality and effectiveness [164,165]. With constraints from absolute geochronologic anchors, this approach can improve the prediction of favorable intervals and fairways for hydrocarbon accumulation, thereby supporting more efficient exploration and develop-

ment. It also provides a basis for linking paleoclimate variability with geological records in marginal sea-linked lacustrine systems [166].

6. Conclusions

This study proposes a conceptual model that links hydrological conditions in the Bohai Bay Basin to astronomically forced climate variability. This work highlights the combined roles of obliquity and eccentricity in regulating hydroclimate in a marginal sea-proximal setting. Under the superposition of multiple orbital parameters, monsoon circulation periodically mediates marine influence on the paleo-Dongying Lake Basin. The main conclusions are as follows:

- (1) From a sedimentological and paleoenvironmental perspective, cyclostratigraphic frameworks based on the patterns and amplitudes of GR logs, mineral abundances, elemental concentrations, and diagnostic elemental ratios—astronomically tuned to the ~405 kyr, ~100 kyr, and ~40 kyr bands—provide robust chronological constraints for the mid-late Eocene lithostratigraphic succession.
- (2) Recognition of a ~1.2 Myr long-obliquity-modulated cycle within the sedimentary “noise” series reveals that lake-level fluctuations in this mid-late Eocene marginal sea-influenced system are strongly paced by astronomical forcing. Monsoon-driven circulation likely amplifies the potential marine influence, thus intensifying the hydrological coupling between the sea and the lake.
- (3) Regional climate variability during the mid-late Eocene is governed by forcing associated with eccentricity and obliquity. Warm and humid conditions preferentially occur during intervals of coupled high eccentricity and high obliquity. Obliquity-driven forcing modulates East Asian hydroclimate cyclicity by regulating the intensity of the East Asian summer monsoon, potentially promoting a northward migration of the ITCZ. A reinforced cross-equatorial insolation gradient and pressure contrast facilitate moisture transport into the Northern Hemisphere during boreal summer. High-latitude ice sheets may further exert feedback effects within the climate system. Moreover, the superposition of orbital bands likely induces hydroclimate oscillations through nonlinear climate responses, which, in turn, drives differentiated sedimentary processes.
- (4) By modulating monsoonal precipitation, eccentricity and obliquity periodically force lake-level fluctuations, water-column stratification, and terrigenous input. Under a coupled “high productivity–anoxic preservation” mode, these changes favor the accumulation of organic-rich shales. Climate-controlled rhythmic alternations between carbonate precipitation and detrital supply give rise to interbedded carbonate and organic-rich argillaceous facies, leading to the concurrent occurrence of high-organic-matter content, brittle mineral enrichment, and pore development in specific lithofacies. This coupling ultimately governs the spatiotemporal distribution and enrichment patterns of shale-oil sweet spots.

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Article

Hydrocarbon-Generating Assemblages and Organic Matter Accumulation Patterns from the Basal Silurian Renheqiao Formation in Western Yunnan, China

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Abstract

The organic-rich shales of the Upper Ordovician–Lower Silurian Renheqiao Formation in Yunnan, China, represent a valuable target for understanding marine hydrocarbon systems and offshore oil and gas exploration. To decipher its organic matter (OM) accumulation patterns and offer perspectives relevant to the assessment of marine resources, this study employs an integrated petroleum geological, sedimentological, and palynological approach. Our findings indicate that organic-rich intervals (cumulative thickness 74–84.5 m) are concentrated in the R1–lower R6 and upper R6–R9 graptolite biozones, exhibiting high total organic carbon (TOC) content and graptolite reflectance values indicative of high to post-maturity thermal evolution, which confirms significant shale gas potential. Sedimentary evolution shows broad similarities with the Yangtze region’s Longmaxi Formation but with finer-scale differences. Due to its restricted paleogeographic setting on the Sibumasu Block, the Baoshan region responded to global sea-level changes with a lag, favoring sustained OM accumulation. Palynological analysis identified microphytoplankton, acritarchs, macroalgae, and animal-derived OM. Hydrocarbon-generating assemblages are divided into three stages: the first (R1–lower R6) and third (upper R6–R9) stages are favorable intervals with high TOC, dominated by microphytoplankton and acritarchs; the second stage (middle R6) shows lower enrichment, with increased macroalgae/animal-derived debris. Our analysis indicates that high abundances of primary producers (microphytoplankton/acritarchs) are strongly associated with organic enrichment. In contrast, higher abundances of secondary consumers (e.g., graptolites) show a significant negative correlation with TOC, suggesting their presence may coincide with conditions less favorable for accumulation or that they actively inhibit it.

Keywords: hydrocarbon-generating organisms; ocean resource; Renheqiao Formation; organic matter accumulation; sedimentary evolution

1. Introduction

The evolution of the Proto-Tethys Oceanic realm holds keys to understanding marine hydrocarbon systems and offers valuable analogues for modern marine offshore hydrocarbon exploration. The Ordovician–Silurian black rock series is extensively developed

in China. The Renheqiao Formation (Fm.) represents a thick sequence of organic-rich, graptolitic black mudstone/shale deposited during this period [1,2]. Tectonically, it belongs to the Sibumasu Block (also known as the Shan–Thai–Malay Block), which was situated near the northern margin of the Gondwana continent during the Late Ordovician to Early Silurian, positioned along the periphery of the Proto-Tethys Ocean between the Arabian Craton and South China [3]. Its paleogeographic location aligns with globally significant hydrocarbon source rock depositional settings and occupied a low-latitude region highly favorable for source rock deposition [4–6]. Current research on organic matter enrichment in the Renheqiao Fm. indicates that its depositional environment can be characterized by a warm and humid paleoclimate, which promoted intense chemical weathering. This weathering process delivered abundant terrigenous nutrients to the ocean, stimulating high primary productivity and thereby providing a substantial source of organic material. Concurrently, a persistently anoxic sedimentary environment effectively inhibited the degradation of organic matter, creating essential conditions for its enrichment and preservation, and the kerogen is primarily composed of Type I to II₁ organic matter, indicating substantial shale gas potential [7,8]. However, comprehensive geological evaluation of the Renheqiao Fm. for shale gas exploration remains incomplete, and fundamental geological research is still in its nascent stages.

Hydrocarbon-generating organisms, as the original source material for petroleum generation, serve as a robust proxy for analyzing hydrocarbon generation potential [5,9]. Variations in hydrocarbon contributions from different organisms render the analysis of hydrocarbon-generating organism assemblages crucial for evaluating highly mature source rocks [10,11]. Over the past decade, significant breakthroughs in the exploration and development of the graptolite-bearing black mudstones/shales of the Wufeng–Longmaxi (WF–LM) Fm.s around the Sichuan Basin have been achieved [12]. Extensive geobiological research on the WF–LM Fm.s has revealed diverse life forms and hydrocarbon-generating organism assemblages during this period [11,13,14], leading to new perspectives on primary hydrocarbon deposition [15,16]. Therefore, systematically analyzing the types of hydrocarbon-generating organism assemblages within the Renheqiao Fm. black mudstones and investigating OM sources have significant implications for precise petroleum resource assessment.

Post-extinction ecological recovery following the end-Ordovician mass extinction was a complex process. Environmental changes have triggered significant shifts in biogeographic distribution. Biodiversity began a gradual recovery during the early Silurian, marked by the emergence of new biological groups and ecological niches [17]. The primary focus of hydrocarbon-generating organism research lies in identifying biological individuals or fragments within source rocks [18,19]. Palynofacies analysis traces the biological origins of maceral components based on the organic petrographic classification of source rocks. Over the past three decades, integrating palynofacies with other datasets has significantly contributed to analyzing hydrocarbon-generating assemblages, interpreting paleoenvironments, and evaluating energy potential [19]. The widely adopted classification of palynological OM relies on observations under transmitted light and fluorescence microscopy. Similar to kerogen analysis, the morphology, texture, and structure of organic macerals serve as key classification criteria [20–22]. The positive correlation between various producers and primary productivity is well-proved [23–25]. However, regarding animals as significant components of hydrocarbon-generating organisms, current research has not yet clearly determined whether secondary productivity substantially contributes to the final quantity of buried OM [26]. This issue requires further investigation through multi-faceted approaches and diverse methodologies, thus highlighting the necessity of focusing on the characteristics and distribution patterns of hydrocarbon-generating or-

ganism assemblages. From an ecological structure perspective, phytoplankton not only serves as primary producers but also provides food sources for zooplankton, filter feeders, and scavengers. Its diversity profoundly influences the enrichment of OM associated with secondary productivity [27]. For instance, in some study areas, a significant portion of primary productivity is consumed by animals such as radiolarians, sponges, and foraminifera, resulting in lower OM enrichment in intervals where primary producers (e.g., acritarchs and algae) are relatively abundant [28,29].

Furthermore, this study adopts an integrated approach that combines the identification and classification of palynomorphs—direct indicators of OM origins—with a comprehensive evaluation of diverse particulate organic components, including amorphous organic matter (AOM) and structured organic matter (SOM). This methodology provides deeper insights into hydrocarbon-generating organisms and allows for a more precise reconstruction and delineation of hydrocarbon generation potential across distinct stratigraphic intervals.

In summary, as a source rock deposit situated along the Proto-Tethys margin under distinct paleogeographic and depositional environments, the composition, interrelationships, and distribution patterns of hydrocarbon-generating organisms within the Renheqiao Fm. are expected to differ from those of the Ordovician-Silurian black rock series (Longmaxi Fm.) in South China. Given that interactions between paleo-oceanic physicochemical and biological environments fostered unique ecosystems fundamentally controlling hydrocarbon-generating organisms and potential, this study analyzes the characteristics of hydrocarbon-generating organism assemblages in the Renheqiao Fm., their distribution patterns, and their interactions with the environment.

2. Geological Settings

The study area is situated within the Baoshan Block (Figure 1), the Chinese segment of the Sibumasu Block (also known as the Shan–Thai–Malay Block), which is a well-known stable continental block [30]. The Sibumasu Block extends from northern Sumatra through western Malaysia and Thailand to the Shan Plateau of Myanmar, and continues northward to the Baoshan Block in China, where it connects with the South Qiangtang Block of Tibet [3,23]. Our investigated strata are located in the central part of the Baoshan region [31]. Paleozoic and Mesozoic strata are well-developed in this area, characterized by abundant fossils and a complete stratigraphic sequence. The Upper Ordovician–Lower Silurian systems are divided, in ascending order, into the Pupiao Fm., Renheqiao Fm., and Lichaiba Fm., all of which exhibit good development.

The Renheqiao Fm. has outcrops in the Baoshan, Lushui, Fengqing, Shidian, and Zhenkang areas of Yunnan Province. It consists of a set of black, graptolite-rich, slope-basin facies rocks deposited in a deep-water environment, displaying well-developed horizontal bedding. Positioned between the Upper Ordovician Pupiao Fm. and the Middle–Upper Silurian Lichaiba Fm., the Renheqiao Fm. therefore provides favorable structural conditions for shale gas development. The Pupiao Fm. comprises variegated marlstones, mudstones, and fine-grained clastic rocks with considerable thickness. The Lichaiba Fm. is dominated by marlstones and limestones, approximately 200 m thick. The Renheqiao Fm. primarily consists of gray, gray-black, and yellowish-brown Graptolite-bearing shales and arenaceous shales. It exhibits well-developed horizontal bedding, contains abundant pyrite grains or lenses, is rich in graptolite fossils, and possesses high OM content, making it a regionally significant source rock. The Renheqiao Fm. can be broadly divided into two members: the lower member consists of black organic-rich siliceous mudstone (shale), and the upper member comprises gray and gray-green silty mudstones and fine-grained detrital rocks. Based on high-resolution graptolite fossil investigations [31–33], nine graptolite biozones, ranging from the Upper Ordovician Hirnantian Stage to the Telychian Stage of

the Silurian Llandovery Series, have been identified within the Renheqiao Fm. These were documented at the Chadi and Banpo sections, located in Renheqiao Town (24°43'48" N, 99°10'48" E) [34]. In ascending order, these are the *Metabolograptus persculptus* Zone (abbreviated R1), *Akidograptus ascensus* Zone (R2), *Parakidograptus acuminatus* Zone (R3), *Cystograptus vesiculosus* Zone (R4), *Coronograptus cyphus* Zone (R5), *Demirastrites triangulatus* Zone (R6), *Lituigraptus convolutus* Zone (R7), *Stimulograptus sedgwickii* Zone (R8), and *Spirograptus guerichi* Zone (R9) [34]. Comparison with the graptolite biostratigraphy of the Longmaxi Fm. in the Yangtze region revealed that these nine graptolite zones in the Baoshan Block's Renheqiao Fm. correspond well to the LM1–LM9 graptolite zones of the Longmaxi Fm. (Figure 1). Consequently, the principal part of the black organic-rich siliceous mudstone (shale) in the Renheqiao Fm. can be correlated with sub-members 2–8 of the lower Longmaxi Fm., equivalent to the primary target interval for shale gas exploration and development in the Fuling area [35,36]. However, the Renheqiao Fm. lacks deposits equivalent to the black siliceous mudstone (shale) of the Wufeng Fm. developed in the Middle-Upper Yangtze region. Instead, the variegated mudstone at the top of the Pupiao Fm. in the Shidian area is stratigraphically equivalent to the Wufeng Fm. of the Middle-Upper Yangtze region.

System	Series	Stage	Formation	South China (Xu et al., 2000)	Formation	Chadi Section (Zheng et al., 2025)	Banpo Section (Zheng et al., 2025)	CPT drill core (this study)	SLJ drill core (this study)
Silurian	Llandovery	Telychian	Longmaxi	N2 <i>Spirograptus turriculatus</i>	Renheqiao				
				LM 9/N1 <i>Spirograptus guerichi</i>		R9 <i>Spirograptus guerichi</i>	R9 <i>Spirograptus guerichi</i>	R9 <i>Spirograptus guerichi</i>	
		Aeronian		LM 8 <i>Stimulograptus sedgwickii</i>		R8 <i>Stimulograptus sedgwickii</i>	R8 <i>Stimulograptus sedgwickii</i>	R8 <i>Stimulograptus sedgwickii</i>	
				LM 7 <i>Lituigraptus convolutus</i>		R7 <i>Lituigraptus convolutus</i>	R7 <i>Lituigraptus convolutus</i>	R7 <i>Lituigraptus convolutus</i>	
				LM 6 <i>Demirastrites triangulatus</i>		R6 <i>Demirastrites triangulatus</i>	R6 <i>Demirastrites triangulatus</i>	R6 <i>Demirastrites triangulatus</i>	
				LM 5 <i>Coronograptus cyphus</i>		R5 <i>Coronograptus cyphus</i>	R5 <i>Coronograptus cyphus</i>	R5 <i>Coronograptus cyphus</i>	
				LM 4 <i>Cystograptus vesiculosus</i>		R4 <i>Cystograptus vesiculosus</i>			
				LM 3 <i>Parakidograptus acuminatus</i>		R3 <i>Parakidograptus acuminatus</i>			
				LM 2 <i>Akidograptus ascensus</i>		R2 <i>Akidograptus ascensus</i>			
				Ruddanian					
Ordovician	Upper Ordovician	Hirnantian	Guanyinqiao	LM 1 <i>Normalograptus persculptus</i>	Pupiao	R1 <i>Metabolograptus persculptus</i>			
				WF4 <i>Normalograptus extraordinarius</i>					
		Katian	Wufeng	WF3 <i>Paraorthograptus pacificus</i>					
				WF2 <i>Dicellograptus complexus</i>					
				WF1 <i>Foliomena-Nankinolithus</i>					

Figure 1. Graptolite zone comparison between the Renheqiao Fm. and the Longmaxi Fm [12,34].

The Chadi section is administratively located approximately 3 km west of Renheqiao Town, Shidian County, Baoshan City, Yunnan Province, China (Figure 2). It is a freshly exposed artificial roadcut profile with excellent outcrop conditions, clear stratigraphic sequences, and abundant graptolite fossils. The Ordovician-Silurian strata in the section

comprise, in ascending order, the Pupiao Fm. and the Renheqiao Fm. The contains six graptolite biozones (Figure 3): the R1 Zone corresponds to the Late Ordovician Hirnantian Stage, the R2–R5 zones correspond to the Silurian Rhuddanian Stage, and the R6 Zone corresponds to the Aeronian Stage [34]. The section is divided into 10 lithologic beds. Bed 1 belongs to the Pupiao Fm. and consists of yellowish-green, thin- to medium-bedded, bioclastic calcareous mudstone containing calcareous concretions. Its overall field character is characterized by alternating purplish-red silty mudstone and grayish-green mudstone representing the Katian age. Beds 2–3 represent the Hirnantian strata: Bed 2 is a paleocrust of weathering showing parallel unconformity with the overlying and underlying strata, and Bed 3 consists of argillaceous siltstone. Beds 4–10 belong to the Renheqiao Fm., dominated by black thin-bedded carbonaceous mudstone and black thin-bedded silty mudstone (Figure 3).

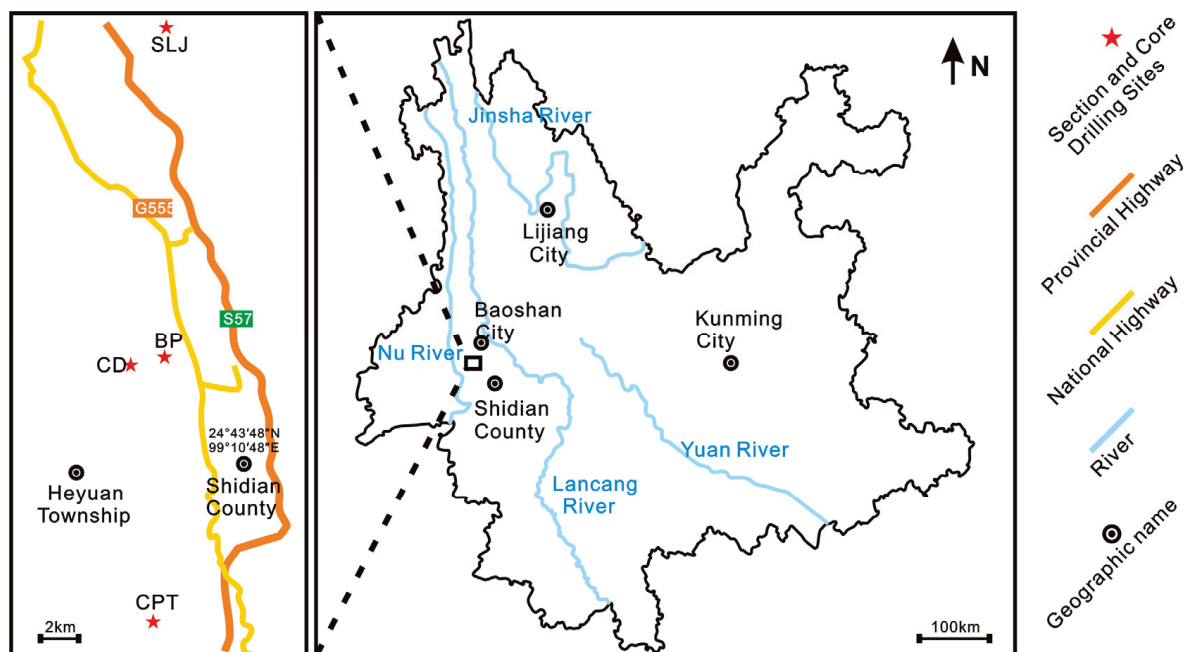


Figure 2. Location maps of the investigated area (CD = Chadi section, BP = Banpo section, CPT = Changputang borehole; SLJ = Shanglongjing borehole).

The Banpo section is located west of Banpo Village, approximately 3 km west of Renheqiao Town and about 1.8 km from the Chadi section (Figure 2). It serves as the type section for the Renheqiao Fm. This section is a freshly exposed artificial roadcut profile with excellent outcrop conditions, a clear stratigraphic sequence, and abundant graptolite fossils. The entire section, from base to top, belongs to the Silurian Renheqiao Fm. It contains four graptolite biozones: the R6, R7, and R8 zones correspond to the Aeronian Stage of the Llandovery Series, and the R9 Zone corresponds to the Telychian Stage (Figure 3). Lithologically, it is divided into eight beds. Beds 1–2 are dominated by gray carbonaceous silty mudstone, locally interbedded with thin siltstone layers. Weathering surfaces appear light yellow, while fresh surfaces are grayish-black. Starting from Bed 3 upwards, the carbon content increases, dominated by silty carbonaceous mudstone.

The Changputang borehole is situated 14.3 km south of Banpo Village (Figure 2). The strata of the Renheqiao Fm. in this area exhibit a relatively horizontal attitude, making it highly suitable for drilling and coring. This borehole penetrated starting from the overlying Lichaiba Fm., reaching the underlying Renheqiao Fm. (Figure 3). Graptolite fossils are abundant, allowing the identification of five graptolite biozones: the R5 Zone corresponds to the Silurian Rhuddanian Stage, the R6–R8 zones correspond to the Aeronian Stage, and the R9

Zone corresponds to the Telychian Stage. The core is divided into seven lithostratigraphic units. Bed 1 is characterized by light gray and yellowish-gray thick-bedded argillaceous siltstone. Beds 2 to 7 form the main part of the section, corresponding to the Renheqiao Fm. The lower part (Beds 2–4) consists mainly of black and gray carbonaceous silty shale and mudstone. The upper part (Beds 5–7) comprises primarily gray and grayish-white thin-bedded argillaceous siltstone and silty mudstone; well-developed horizontal bedding and lamellation are present (Figure 3).

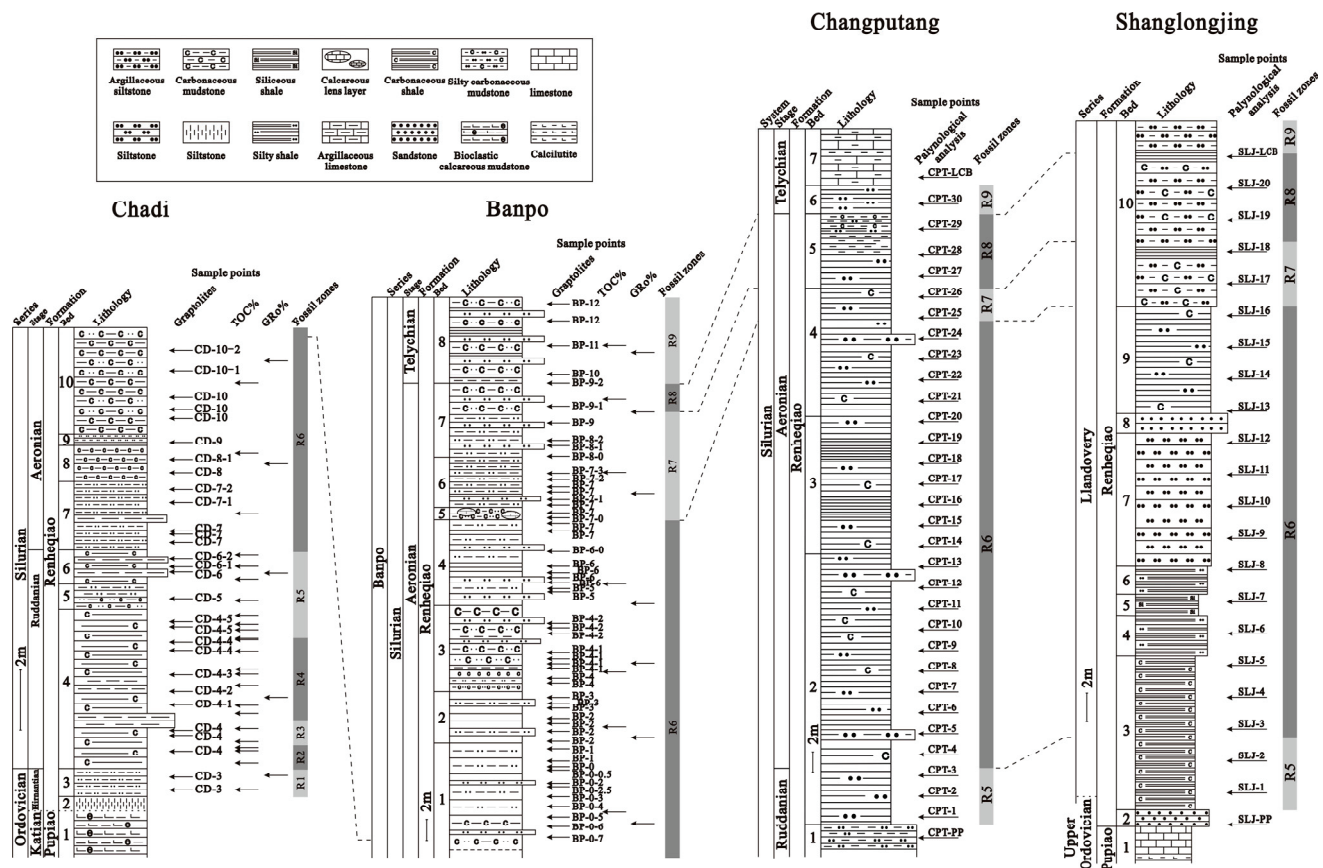


Figure 3. Stratigraphic correlations and sample points of the investigated sequences.

The Shanglongjing borehole is located near Shanglongjing Village, Laomai Township, approximately 18.1 km north of Banpo Village. The core sampling condition is excellent. The boundary between the Renheqiao Fm. and the underlying Pupiao Fm. is distinct, while the boundary with the overlying Lichaiba Fm. is less clear. Five graptolite biozones were identified: the R5 Zone corresponds to the Silurian Rhuddanian Stage, the R6–R8 zones correspond to the Silurian Aeronian Stage, and the R9 Zone corresponds to the Telychian Stage (Figure 3). The core is divided into 10 lithologic beds. Bed 1 consists of silty limestone with mud crystals and calcilitite, featuring horizontal bedding and containing shelly bioclastic as well as calcite veins. This bed corresponds to the Upper Ordovician Pupiao Fm. Bed 2 marks the entry into the Renheqiao Fm., composed of dark gray sandstone interbedded with thin marl layers. Beds 3 to 6 comprise grayish-black to black carbonaceous shale with well-developed horizontal bedding and abundant graptolites. Beds 7 to 10 show an increase in silt content, dominated by silty carbonaceous mudstone, occasionally displaying horizontal or lenticular siltstone layers; minor pyrite is developed and graptolite fossils are present (Figure 3).

3. Materials and Methods

3.1. Graptolite Sampling

To determine the geological ages of the four investigated sequences, systematic graptolite sampling was conducted following the principle of representative coverage across all lithologies. Collected samples were subsequently identified in the laboratory. The sampling quantities were as follows:

Changputang core: 470 samples.

Shanglongjing core: 441 samples.

For the Chadi and Banpo sections where graptolites are well-preserved and reported [34], statistical analyses of graptolite abundance and diversity were performed using a vertical sampling interval of 1.6 m.

3.2. TOC and Graptolite Reflectance Analysis

TOC abundance analyses were conducted relatively on 7 samples from the Banpo section and 20 samples from the Chadi section distributed uniformly throughout the Renheqiao Fm. (sample points shown in Figure 3). TOC abundance was determined by a Carbon/Sulfur Analyzer CS-2000 (LECO Corporation, St. Joseph, MI, USA) after dissolution of powdered samples in 10% HCl and subsequent air drying. This was performed at the Wuxi Research Institute of Petroleum Geology, China, with an analytical precision better than $\pm 0.2\%$.

Samples for reflectance measurement were collected from the Renheqiao Fm. The sampling quantities were as follows: 5 samples from the Chadi section, 7 samples from the Banpo section, data from the Changputang and Shanglongjing borehole cores are cited from [2] (Table 1). Samples were gently crushed using a jaw crusher and sieved to obtain particles ranging from 10 to 20 mesh (2–0.9 mm). These particles were mounted with epoxy resin into cylindrical blocks approximately 1 cm in diameter. After grinding and polishing, a smooth surface containing numerous fine rock particles was prepared. Reflectance measurements were conducted under oil immersion using a Leica DM4500P polarizing microscope (Leica Microsystems, Wetzlar, Germany) with a 50 $\times$ objective, and random reflectance values were recorded. Due to the fine-grained nature of bitumen particles in the shale, a grayscale-based method for OM reflectance calculation was employed [9,37]. Graptolite reflectance (GRo) is a well-established proxy for thermal maturity assessment in Silurian strata lacking vitrinite. To calculate an equivalent vitrinite reflectance (EqVRo), we applied the conversion formula $\text{EqVRo} = 0.99 \times \text{GRo} + 0.08$ [38], with results summarized in Table 1. It is important to note the inherent constraints of this approach: (1) the conversion is empirical, and EqVRo may diverge from true vitrinite reflectance, particularly at thermal maturity extremes; and (2) for outcrop samples, surficial weathering may have caused minor oxidation or alteration of the graptolite periderm, potentially leading to a slight underestimation of GRo and, consequently, EqVRo. The graptolites in the Renheqiao Fm., though often fragmented and variably preserved within the mineral matrix, provided consistent material for measurement, primarily derived from their cortical tissues [39,40]. The potential implications of these constraints for data interpretation are addressed in the Discussion (Section 5.1).

Table 1. Graptolite reflectance and equivalent vitrinite reflectance in the investigated sequences (data from the Changputang and Shanglongjing borehole cores are cited from [2]).

Sampling Location	Sampling Quantity	Graptolite Reflectance GRo (%)	Equivalent Vitrinite Reflectance EqRo (%)
Chadi	5	1.16	1.23
Banpo	7	1.54	1.60
Changputang	10	1.77	1.83
Shanglongjing	16	1.86	1.92

3.3. Palynological Analysis

To investigate hydrocarbon-generating organisms and OM composition, fresh core samples from the Changputang and Shanglongjing boreholes were selected for experimental analysis (sample points shown in Figure 3). Sample processing followed standard palynological preparation techniques as outlined by Tyson (2000) and Traverse (2007) [41,42]. All samples were first cleaned to eliminate potential contamination by mechanically removing weathered surfaces with a chisel and hammer, then crushed into 2–5 mm fragments. Subsequently, 25 g aliquots of each sample were subjected to sequential chemical treatments: carbonates were dissolved using 37% HCl (18 h), followed by silicate removal with 40% HF (24 h), to concentrate acid-insoluble organic components for analysis.

To quantify the OM content in each sample, a tablet containing a fixed concentration of *Lycopodium* spores (27,637 spores/tablet) was dissolved in acid, allowing the spores to disperse uniformly in the solution for statistical normalization of particle counts. Between processing steps, samples were rinsed with distilled water until the rinse water reached pH neutrality. Following this procedure, a mixed solution of ZnI₂ and KI (density: 2.15–2.25 g/cm³) was added, stirred, and centrifuged to separate the OM. The material floating on the surface was carefully extracted, washed, and transferred to distilled water. Finally, strew slides were prepared using the concentrated organic residue.

Quantification of organic particles was conducted using strew slides. Each slide was studied and photographed under transmitted white light with a Leica DM5500 biological microscope (Leica Microsystems, Wetzlar, Germany) at the State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences (Wuhan). Palynomorphs were identified and recorded based on their occurrence in each slide, as quantitative analysis of palynomorph types is inherently subject to depositional and preservation biases [42]. For each sample, counting was terminated once exactly 70 *Lycopodium* spores were tallied. AOM and SOM were quantified by counting discrete particles, with a particle defined as any organic fragment whose approximate area was equivalent to a circle 45 µm in diameter.

The raw counts were subsequently extrapolated to the whole-sample scale using Formula (1):

$$OM_{CON} = \frac{N \times C_{ly}}{N_{ly}} \quad (1)$$

where OM con: OM concentration (pieces/25 g), N: counted OM numbers (pieces), C_{ly}: *Lycopodium* spore concentration (27,637 pieces/25 g), and N_{ly}: counted *Lycopodium* spore numbers (pieces). *Lycopodium* spores were used as a normalization factor of each kind of OM. All figured specimens are stored in specimen room 812 in the main building in China University of Geosciences (Wuhan).

4. Results

4.1. The Abundance and Diversity of Graptolites

4.1.1. Abundance

To quantify graptolite abundance, specimen counts per unit area (1600 cm²) were measured in the Chadi and Banpo sections. Statistical analysis of 18 sampling bins (3.3 m each) revealed significant vertical variation in abundance within the Renheqiao Fm., showing an overall downward trend from base to top. Peak abundance (>200 specimens/1600 cm²) occurred at the lower part of Aeronian in R6 Zone, while the R7 Zone recorded the minimum (six specimens/1600 cm²) (Figure 4).

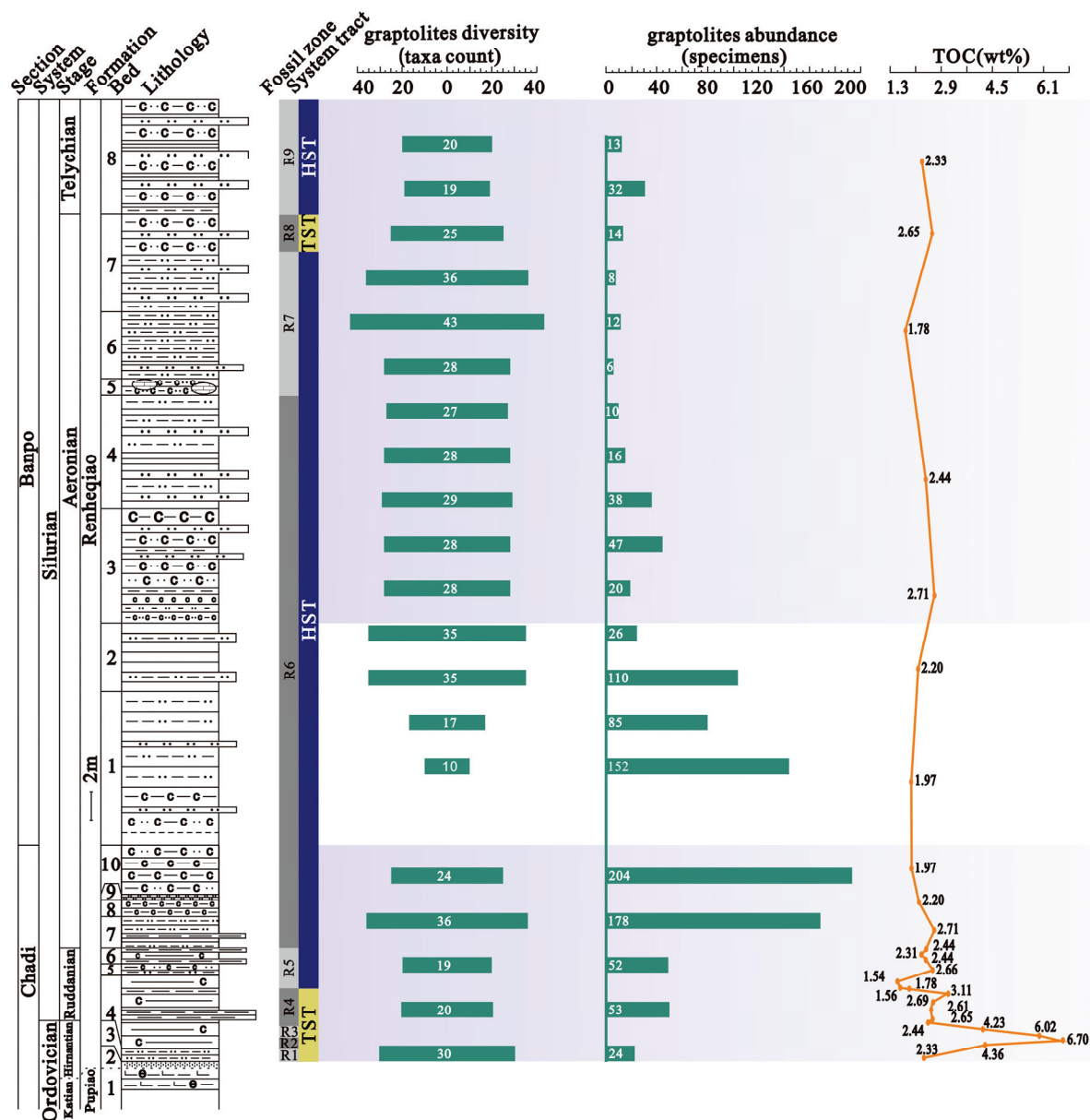


Figure 4. Composite column of the Chadi and Banpo sections, showing graptolite abundance, diversity, and TOC% (Legend same as in Figure 3).

In the lower Hirnantian strata of the Chadi section (Bed 3), lithologically dominated by gray-black thin-bedded silty mudstone, the interval yields graptolites including *Metabolograptus persculptus*, *M. ojsuensis*, *M. extraordinarius*, and *Normalograptus xainzaensis* [32], and the graptolite abundance is 24 specimens per unit area, representing moderate values within the section. In the overlying Rhuddanian strata (Beds 4–6), lithologically dominated by black thin-bedded carbonaceous shale intercalated with thin (3–5 cm) mudstone layers, the interval exhibits upward-increasing silt content and well-developed horizontal laminae. It yields graptolites including *Akidograptus ascensus*, *Metabolograptus wangjiawanensis*, *Parakidograptus acuminatus*, *Normalograptus scalaris*, *Cystograptus vesiculosus*, *N. similis*, and *Coronograptus cyphus* [34]. Graptolite abundance averaged 52.5 specimens per unit area, indicating an increase compared to underlying beds (Figure 4). In the Aeronian strata (Beds 7–10), lithologically dominated by black thin-bedded silty mudstone with silt laminae, the interval yields graptolites including *Demirastrites triangulatus*, *Petalolithus minor*, *Normalograptus crassus*, *Oktavites communis juvenis*, *Monograptus xizangensis*, *Pernerograptus*

revolutus gracilentus, *Demirastrites magnificus*, and *Rastrites guizhouensis* [34]. Graptolite abundance reaches its maximum in this interval, averaging 191 specimens per unit area.

Beds 1–2 of the Banpo section represent the lower R6 Zone, lithologically dominated by gray carbonaceous silty mudstone with locally interbedded thin siltstone layers, showing higher clay content than the upper beds of the Chadi section. The interval yields graptolites including *Emirastrites magnificus*, *Rastrites distans*, *Diplograptus changningensis*, *Monograptus rhynchophorus*, *Streptograptus runcinatus*, *Euclimacograptus hastatus*, *Oktavites spiralis*, *Pristiograptus sichuanensis*, and *Pernerograptus raphidos* [34]. Graptolite abundance remains substantial in this interval, averaging 93.25 specimens per unit area (Figure 4). Beds 3–4 of the Banpo section represent the R6 Zone, dominated by gray-black laminated carbonaceous mudstone with laminae composed of alternating white silty and black clayey layers. This interval yields graptolites including *Pristiograptus concinnus*, *Climacograptus scalaris*, *Rastrites guizhouensis densus*, *Demirastrites denticulatus*, *Oktavites gansuensis*, and *Pernerograptus qijiangensis* [34]. Graptolite abundance shows a marked decline here, averaging 26.2 specimens per unit area (Figure 4). Beds 5–8 of the Banpo section encompass the R7–R9 graptolite zones. Lithologically dominated by gray laminated silty mudstone with laminae composed of alternating white silty and black clayey layers, the interval exhibits upward-increasing clay content. It yields graptolites including *Pristiograptus sichuanensis*, *Demirastrites triangulatus*, *D. decipiens valens*, *Pernerograptus galaensis*, *Monograptus gemmatus*, *Lituigraptus convolutus*, *Rastrites linggispinus*, *Streptograptus cf. nanshanensis*, *S. crisptus*, and *S. linearis* [34]. Graptolite abundance is notably low in this interval, averaging 14.17 specimens per unit area (Figure 4).

4.1.2. Diversity

Based on graptolite taxonomic data from Zheng et al. [34], diversity was calculated at 3.3 m intervals for both the Chadi and Banpo sections. This investigation reveals that graptolite diversity remained relatively stable throughout the Renheqiao Fm. In the Chadi section, diversity shows an upward-increasing trend, peaking at 36 species in Beds 7–8, coinciding with the base of the Aeronian Stage. Similarly, the Banpo section exhibits an upward-increasing diversity pattern: minimum diversity (10 species) occurs in the basal Bed 1, while maximum diversity (43 species) is recorded in Bed 6, corresponding to the mid-R7 Zone (Figure 4).

4.2. Graptolite Reflectance

Thermal maturity in the study area was assessed based on published core data and our own measurements. For the Changputang and Shanglongjing cores, the literature data ([2], Table 1) show G_{Ro} values ranging from 1.53% to 1.89% (average 1.77%) and 1.52% to 2.13% (average 1.86%), respectively, with corresponding average E_{qV}R_o values of 1.83% and 1.92%. Our new measurements from the Chadi and Banpo sections yielded lower G_{Ro} ranges of 1.12–1.20% (avg. 1.16%) and 1.51–1.57% (avg. 1.54%), with calculated average E_{qV}R_o values of 1.23% and 1.60%, respectively (Table 1). It should be noted that the G_{Ro} values from the Chadi and Banpo outcrop sections are slightly lower than those from the borehole cores, which is consistent with the expected effect of surficial weathering (see Section 3.2). Nevertheless, the overall thermal maturity pattern—with the Shanglongjing core showing the highest values and the Chadi section the lowest—remains internally consistent and interpretable.

4.3. TOC Content

As shown in Figure 4, analysis reveals that TOC% in the Chadi section ranges from 1.54% to 6.70% (mean: 2.87%), exhibiting higher values in lower beds and lower values in upper beds. Within the carbonaceous shale interval from the base to the upper part of Bed 4,

TOC% remains high (2.33–6.70%; mean: 3.71%), corresponding to the lower part of biozones R2–R5. From the upper Bed 4 to the top of the section, where silty carbonaceous mudstone or silty mudstone dominates, TOC% decreases significantly (1.54–2.71%; mean: 2.11%), corresponding to the lower R5 Zone through R6 Zone. The average TOC% for the entire Banpo section is 2.24%. The minimum value of 1.78% occurs in Bed 7, corresponding to the R7 zone, while the maximum value of 2.71% is found in Bed 3, which belongs to the R6 zone. Within the R6 zone (Beds 1–4), the average TOC% is 2.33%. From Bed 1 to the lower part of Bed 3, TOC% gradually increases to 2.71%, after which it begins to show a downward trend. Within the R7 zone (Bed 5 to the lower part of Bed 8), the TOC% is 1.78%, representing the lowest value in the section. The R8 Zone corresponds to the upper part of Bed 7, where TOC% increases to 2.65%. The R9 Zone corresponds to Bed 8, with a TOC% of 2.33%.

Previous studies indicate that TOC% content in the Changputang borehole ranges from 0.51% to 2.14%, averaging 0.76%. The Shanglongjing borehole shows an overall TOC% range of 0.91% to 8.21%, with an average content of 4.27% [2].

4.4. Organic-Walled Microfossils and OM Abundance in Palynological Analysis

To explore hydrocarbon-generating organisms in the Renheqiao Fm., microscopic examination was performed on the experimental results of palynological OM from the Changputang and Shanglongjing borehole core. The palynological OM was classified into three categories: ① Organic-walled microfossils are collectively termed palynomorphs, primarily composed of phytoplankton and acritarchs, along with fungal spores (Figures 5 and 6), which were microscopically observed, photographed, and identified. ② Under transmitted light microscopy, SOM comprises dark-colored, opaque fragments characterized by sharp margins and well-defined internal structures, including cuticular sheets and cellular remnants (Figures 7–9). While these particles exhibit distinct morphological organization, their specific internal structures often remain unidentifiable at the observed scale. The advanced degradation stage imparts a dark brown to black color with fragment dimensions variable between 25 and 220 μm . They are mainly derived from macroalgae and animals [20]. Others are some gelified homogeneous masses, the product of the gelification of late-stage diagenesis [26], presenting as rounded or polygonal plates or foam-like structures, with conchoidal or irregular fractures, and appearing colorless, yellow, or orange-red. They are typically brighter than other macerals (Figure 7E–G). ③ Under transmitted light, AOM is transparent or opaque, flocculated or gelatinous, and shows no identifiable biological structure or stable contour (occasionally cell-structure remnants are observed; Figure 10). The opaque AOM (Figure 10a,c) corresponds to black structureless aggregates, and gelatinous transparent amorphous organic matter (TOM), which consists of flocculent or spongy aggregates (Figure 10b,c), most likely corresponding to cyanobacterial mats [20,41,43]. Mixed opaque and (TOM) is abundant in the measured sequences (Figure 10c).

Standardized quantification of the three categories of OM was conducted using the lycopodium-based quantification method (a lycopodium spore, Figure 10c). Palynological OM in both core samples is dominated by AOM, accounting for approximately 97–99% of the total, with minor SOM and diverse palynomorph assemblages.

4.4.1. Changputang

In the Changputang borehole core, the palynomorphs are predominated by micro planktonic algae, notably *Leiosphaeridia*, *Shuiyousphaeridium*, and *Baltisphaeridium*, while specific intervals contain abundant fragments of SOM. The distribution of these components reveals systematic stratigraphic patterns: organic-walled fossil assemblages form three distinct intervals, each characterized by peak abundances of micro phytoplank-

ton and acritarchs, with subsidiary contributions from macroalgae and fungal spores. Based on vertical variations in fossil types and AOM abundance, three hydrocarbon-generating organism assemblages are defined for this borehole, with their OM content concisely documented.

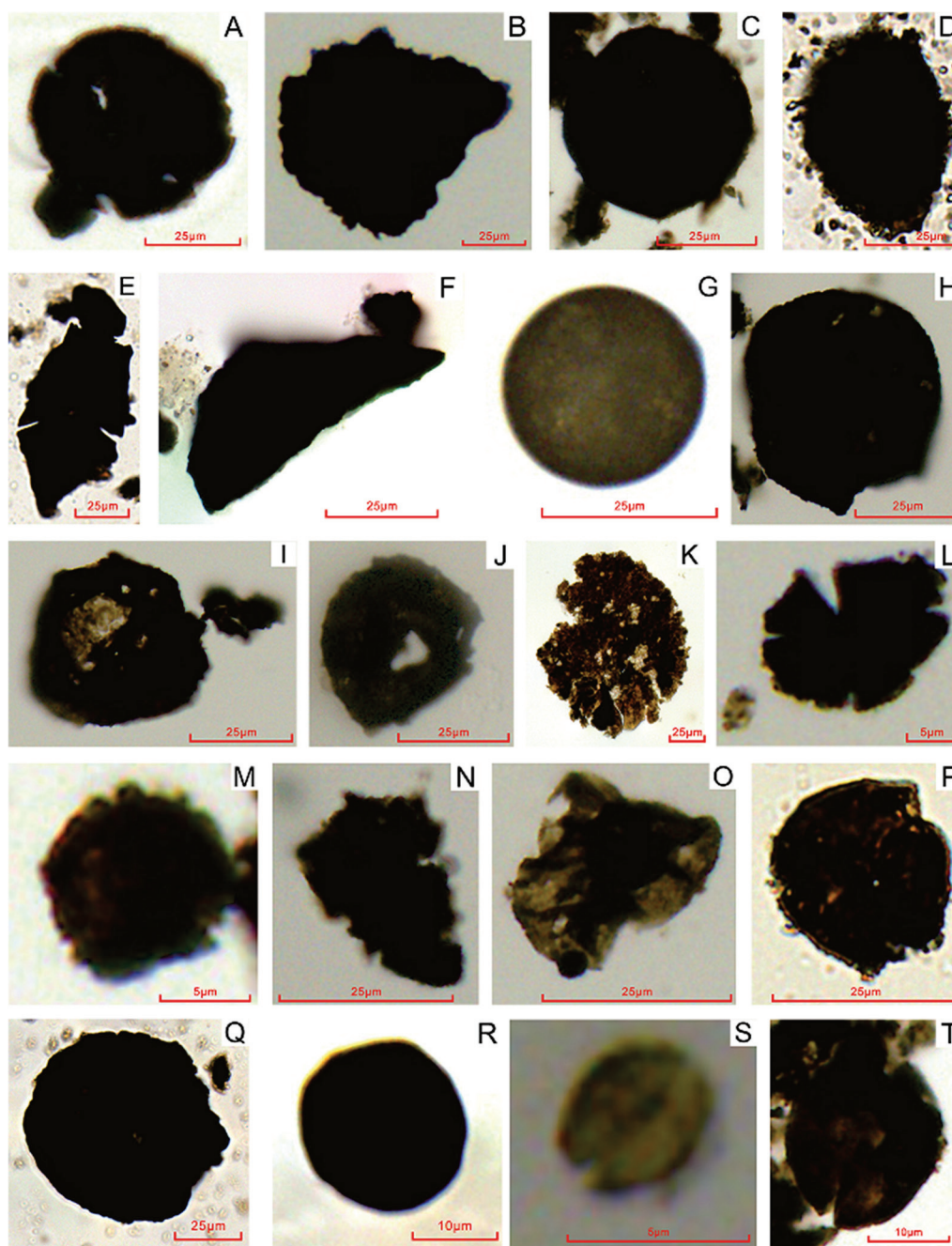


Figure 5. Organic-walled microfossils from the palynological slides of the Renheqiao Fm. in the Changputang core. (A), *Leiosphaeridia atava* from Bed 2 (CPT-11); (B), *Pireia sinensis* Li from Bed 2 (CPT-07); (C), *Leiosphaeridia* sp. from Bed 2 (CPT-11); (D), *Leiosphaeridia* sp. from Bed 4 (CPT-24); (E), *Shuiyousphaeridium macroreticulatum* from Bed 4 (CPT-25); (F), *Triceratim* sp. from Bed 6 (CPT-LCB); (G), fungal spore from Bed 2 (CPT-05); (H,I,K) *Leiosphaeridia* spp. from Bed 2 (CPT-10); (J), *Leiosphaeridia* sp. from Bed 2 (CPT-6); (L), *Protosphaeridium pusillum* from Bed 2 (CPT-12); (M), *Baltisphaeridium* sp. from Bed 3 (CPT-15); (N), *Leiosphaeridia anquiensis* from Bed 3 (CPT-15); (O), *Tetrahedraletes medinensis* from Bed 3 (CPT-15); (P), *Retisphaeridium* sp. from Bed 4 (CPT-25); (Q,R), fungal spore from Bed 3 (CPT-15); (S), *Classopollis monostraitus* from Bed 5 (CPT-27); (T), *Classopollis monostraitus* from Bed 5 (CPT-25).

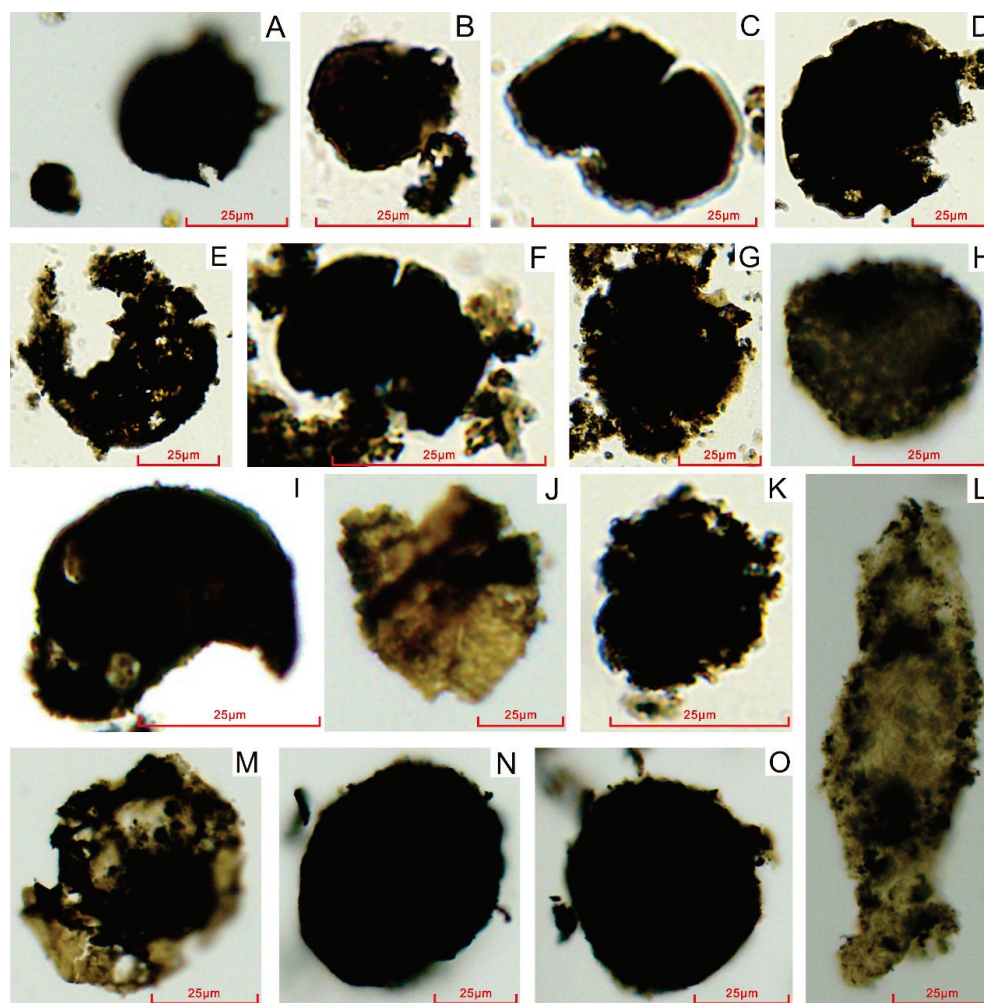


Figure 6. Organic-walled microfossils from the palynological slides of the Renheqiao Fm. in the Shanglongjing core. (A), *Leiosphaeridia* sp. from Bed 3 (SLJ-2); (B), *Visbysphaera microspinosus* from Bed 3 (SLJ-3); (C), subordinate multicellular sporangial fragments from Bed 3 (SLJ-3); (D), *Baltisphaeridium* sp. from Bed 9 (SLJ-15); (E), *Dictyosphaera delicata* from Bed 7 (SLJ-9); (F), *Leiosphaeridia* sp. from Bed 7 (SLJ-10); (G), *Baltisphaeridium* sp. from Bed 10 (SLJ-17); (H), *Arctacellularia ellipsoidea* from Bed 7 (SLJ-11); (I), *Pseudozonosphaera densa* from Bed 7 (SLJ-10); (J), *Meghystrichosphaeridium?* *densum* from Bed 9 (SLJ-14); (K), *Acrosphaeridium sensum* from Bed 9 (SLJ-14); (L), *Shuiyousphaeridium macroreticulatum* from Bed 5 (SLJ-7); (M), *Tetrahedraletes medinensis* from Bed 9 (SLJ-15); (N), *Leiosphaeridia* sp. from Bed 3 (SLJ-4); (O), *Leiosphaeridia* sp. from Bed 3 (SLJ-4).

(1) Interval 1 (samples CPT-01 to CPT-07): Designated as the *Leiosphaeridia* Zone.

This interval corresponds to the lower part of lithologic Bed 2 and is primarily composed of silty shale. Palynomorphs are dominated by black smooth-walled sphaeromorphs (*Leiosphaeridia*, Figure 5), exhibiting bilaterally symmetric circular or elliptical forms with smooth or wrinkled surfaces. Diameters (long axis) range 25–40 μm , occasionally showing monolete structures. Most specimens are indeterminable to species level, though *Leiosphaeridia atava* (Figure 5A) and *L. anquiensis* (Figure 5N) were identified, predominantly preserved in a black to dark brown color. Only four genera and five species were documented. This zone is characterized by overwhelming *Leiosphaeridia* dominance, with subordinate occurrences of *Pireia sinensis* (Figure 5B). Palynomorph concentration averages 1464 pieces/25 g of sediment (variation curve shown in Figure 11).

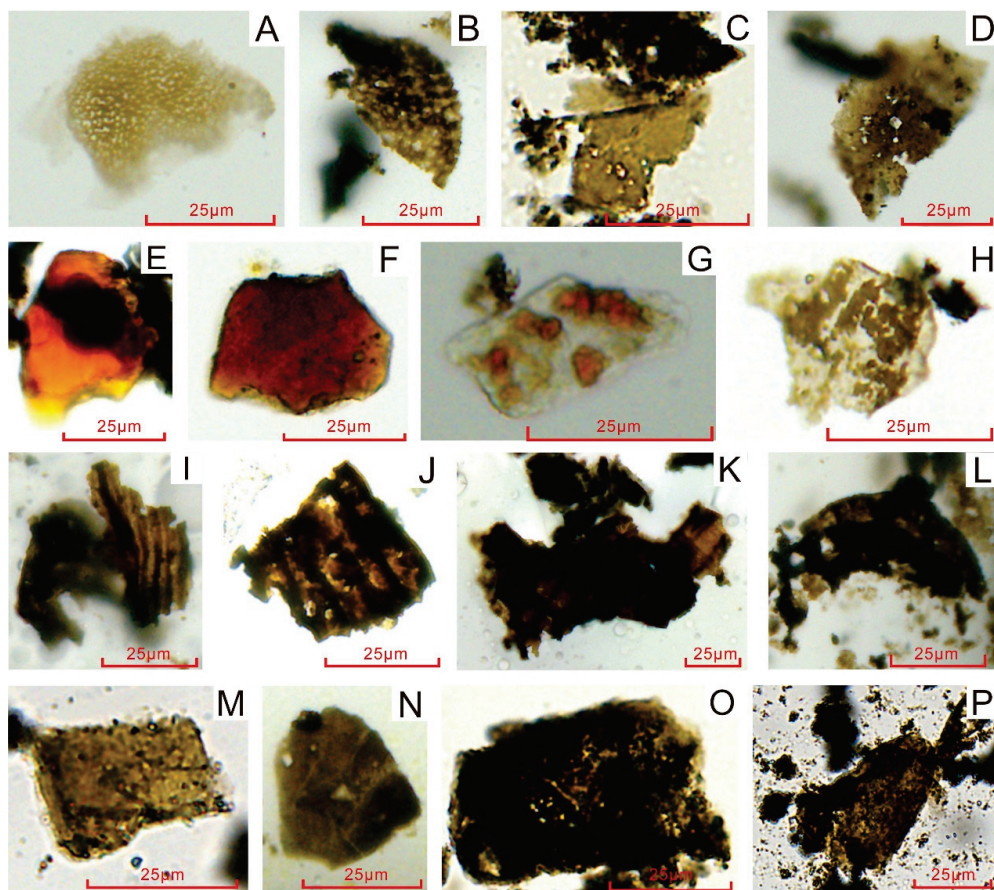


Figure 7. SOM from the palynological slides of the Renheqiao Fm. in the Changputang core. (A), fragment of *Visbysphaera microspinoso* from Bed 2 (CPT-3); (B), fragment of *Baltisphaeridium coolibahense* from Bed 5 (CPT-27); (C), light brown porous organic fragment from Bed 5 (CPT-27); (D), light brown porous organic fragment from Bed 4 (CPT-24); (E,F), homogenized gelified masses from Bed 3 (CPT-17); (G), homogenized gelified masses from Bed 4 (CPT-25); (H), light brown porous organic fragment from Bed 3 (CPT-15); (I,L), light brown porous organic fragment from Bed 3 (CPT-14); (J,P), light brown porous organic fragment from Bed 3 (CPT-20); (K,N), brown membranous biostructured sheets from Bed 2 (CPT-11); (M), light brown porous organic fragment from Bed 4 (CPT-24); (O), light brown porous organic fragment from Bed 4 (CPT-25).

Palynological OM content in this interval is moderate throughout the sequence (Figure 11). AOM primarily consists of flocculent opaque material with minor TOM, averaging 9,097,582.57 pieces/25 g. SOM appears as black or brown fragments, mostly well-defined blocks 70–320 µm in length (Figure 7K,N). Distinct porous structures are observable, featuring pore diameters of 0.8–2 µm (Figure 7A), indicative of macroalgal debris. SOM averages 8935 pieces/25 g.

- (2) Interval 2 (samples CPT-08 to CPT-18): Designated as the *Protosphaeridium-Baltisphaeridium* Assemblage Zone.

This interval spans from the upper part of lithologic Bed 2 to the lower part of Bed 3, and the lithology is dominated by silty shale interlayered with argillaceous shale. Microphytoplankton fossil diversity and abundance show a modest increase compared to the underlying interval 1. A total of seven genera and seven species were identified, dominated by *Protosphaeridium* and *Baltisphaeridium*, with common occurrences of *Shuiyousphaeridium macroreticulatum*, *Baltisphaeridium* sp. (Figure 5M), *Leiosphaeridia anquiensis* (Figure 5N), *Protosphaeridium pusillum* (Figure 5L), and *Tetrahedraletes medinensis* (Figure 5O). This zone also features rare fungal spores (Figure 5Q,R). The assemblage is characterized by abun-

dant animal-derived SOM (Figure 9E), light brown porous fragments of macroscopic algae (Figure 7H,I,L), brown membranous biostructured sheets (Figure 7K,N), and homogenized gelified masses (Figure 7E,F). Palynomorph concentration decreased to 952 pieces/25 g (variation curve shown in Figure 11).

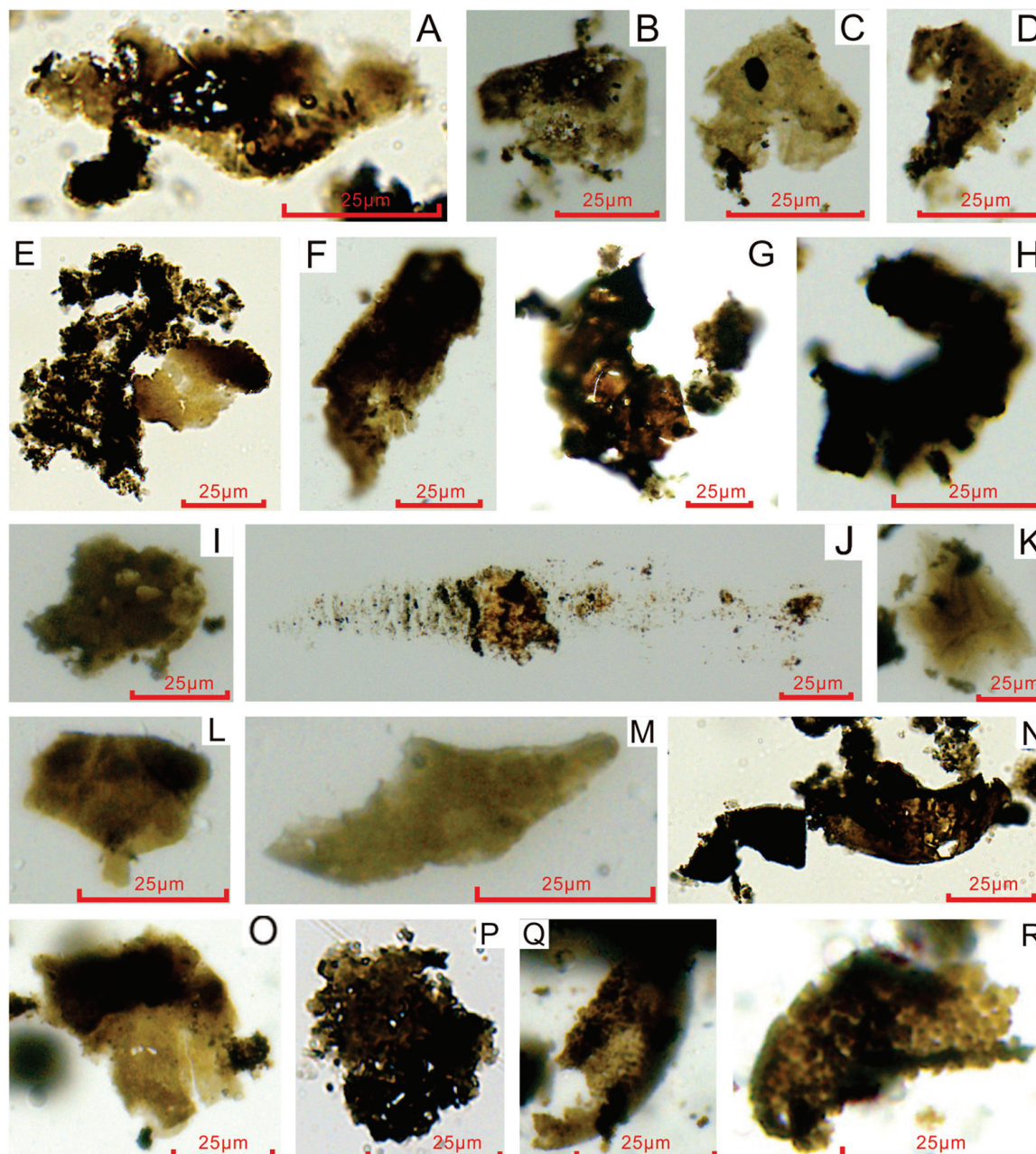


Figure 8. SOM from the palynological slides of the Renheqiao Fm. in the Shanglongjing core. (A), light brown porous organic fragment from Bed 3 (SLJ-2); (B,C), light brown porous organic fragment from Bed 3 (SLJ-4); (D), light brown porous organic fragment from Bed 4 (SLJ-6); (E), filamentous and granular OM fragments from Bed 10 (SLJ-20); (F), brown rod-shaped OM fragment from Bed 7 (SLJ-10); (G), irregular organic fragments from Bed 7 (SLJ-12); (H), brown, curved organic fragment from Bed 9 (SLJ-15); (I), light brown porous organic fragment from Bed 9 (SLJ-14); (J), cylindrical organic fragment with biological structures from Bed 9 (SLJ-14); (K,P), organic fragment with biological structures from Bed 7 (SLJ-12); (L), organic fragment with biological structures from Bed 10 (SLJ-17); (M), organic fragment with biological structures from Bed 10 (SLJ-20); (N), cylindrical OM fragments from Bed 7 (SLJ-11); (O), brown porous organic fragment from Bed 10 (SLJ-17); (Q,R), irregular organic fragments from Bed 10 (SLJ-18).

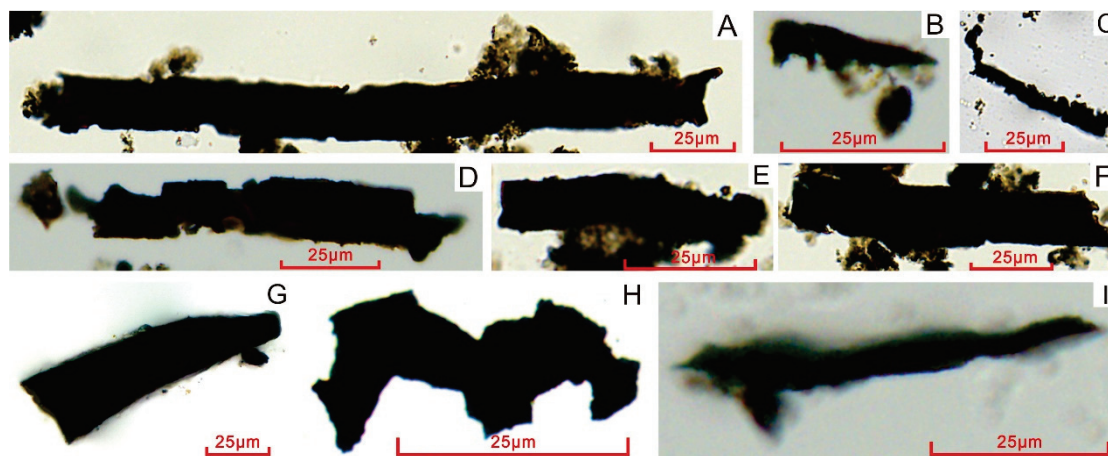


Figure 9. Animal-derived SOM from the Renheqiao Fm. in the Changputang and Shanglongjing cores. (A,D), animal organic lining from Bed 3 (CPT-15); (B), organic inner lining of sponge spicule from Bed 3 (SLJ3); (C,G), organic inner lining of sponge spicule from Bed 3 (CPT-20); (E), animal organic lining from Bed 2 (CPT-11); (F), animal organic lining from Bed 3 (CPT-16); (H,I), animal organic lining from Bed 4 (CPT-24).

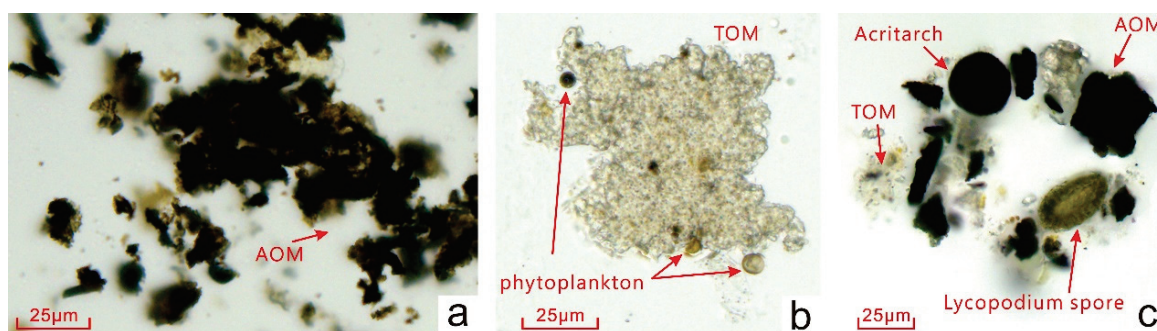


Figure 10. AOM from the Renheqiao Fm. in the Changputang and Shanglongjing cores. (a), opaque AOM from Bed 2 (CPT-3); (b), flocculated TOM from Bed 4 (CPT-23); (c), a mixture of opaque AOM, TOM acritarchs, and lycopodium spores.

In this interval, AOM content decreases significantly, reaching the lowest level in the entire sequence (Figure 11). It is dominated by flocculent and granular opaque material with minor TOM, averaging 5,098,245.36 pieces/25 g. SOM content shows no marked changes, maintaining an average concentration of 14,538 pieces/25 g.

(3) Interval 3 (samples CPT-19 to CPT-30): Designated as the *Shuiyousphaeridium* Zone.

This interval spans from the upper part of lithologic Bed 3 to Bed 6. The lithology of this interval primarily consists of silty shale, with total organic carbon content increasing upward through the sequence, exhibiting the highest microphytoplankton fossil diversity in the borehole, with eight genera and 12 species identified. It is characterized by abundant *Shuiyousphaeridium macroreticulatum* (Figure 5E), accompanied by *Leiosphaeridia* sp., *Visbysphaera microspinosa* (Figure 7A), *Baltisphaeridium* sp., *Meghystrichosphaeridium? densum*, *Acrosphaeridium sensum*, and *Baltisphaeridium coolibahense* (Figure 7B), alongside multicellular sporangial fragments, fungal spores, and *Classopollis monostratus* (Figure 5S). Paly-nomorph concentration averages 1120 pieces/25 g (variation curve shown in Figure 11).

In this interval, AOM content displays an upward-decreasing trend, showing a significant decline within the R8 Zone (Figure 11). It is dominated by granular opaque material with minor TOM, averaging 13,581,837.38 pieces/25 g. SOM content exhibits no significant change, maintaining an average concentration of 13,251 pieces/25 g.

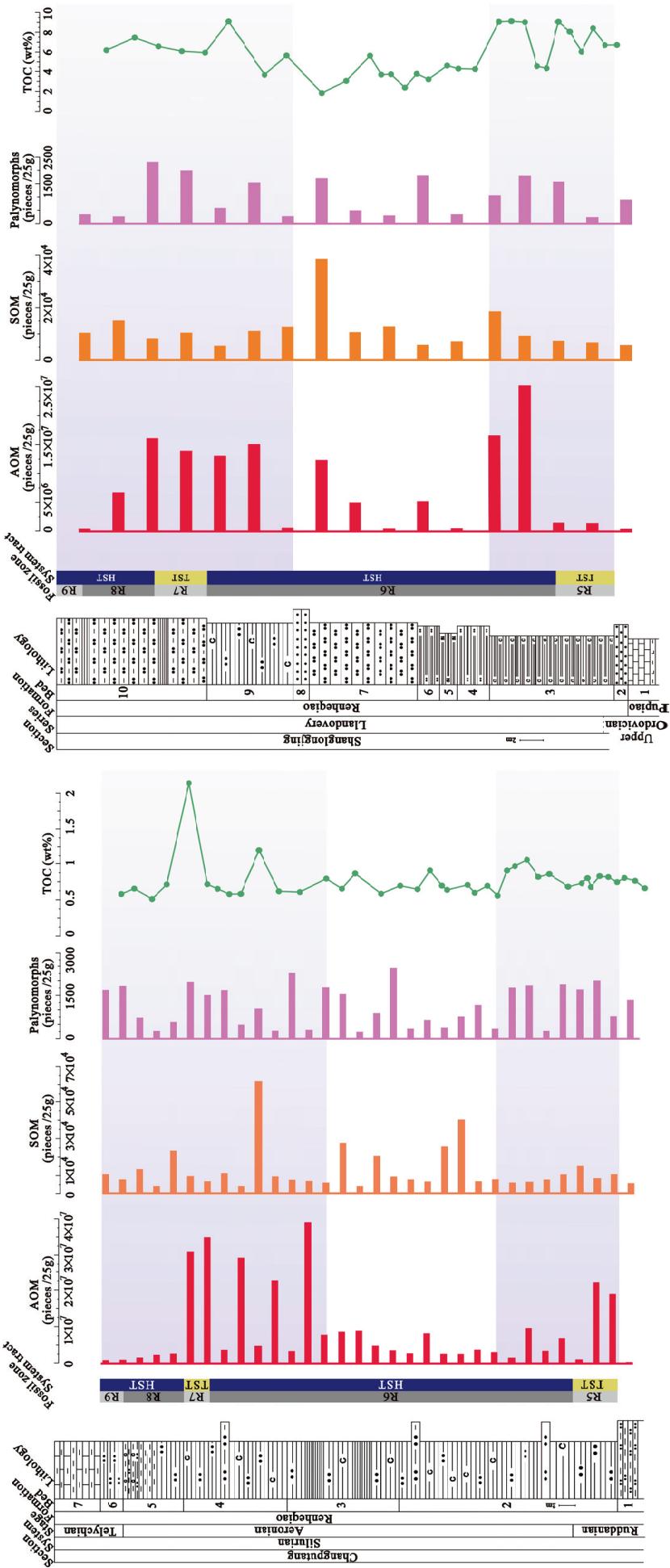


Figure 11. Palynological OM content and TOC% content of the Changputang and Shanglongjing cores (Legend same as in Figure 3. TOC% data cited from [2]).

4.4.2. Shanglongjing

The Shanglongjing borehole core exhibits abundant organic-walled fossils, with microphytoplankton dominated by *Leiosphaeridia*, *Baltisphaeridium*, and *Shuiyousphaeridium*. Significant fragments of macroalgae and animal-derived organic debris occur in specific intervals. Their distribution follows discernible stratigraphic patterns, featuring three distinct palynomorph assemblage and AOM abundance. This trend corresponds to three low-to-high preservation cycles of AOM and shows clear correlation with lithological transitions.

(1) Interval 1 (samples SLJ-01 to SLJ-05): Designated as the *Leiosphaeridia* Zone.

This interval corresponds to lithologic Bed 3, dominated by carbonaceous shale. Palynomorphs are overwhelmingly dominated by black smooth-walled sphaeromorphs (*Leiosphaeridia*), exhibiting bilaterally symmetric circular/elliptical forms, smooth or wrinkled surfaces, and occasional monolete structures, diameters (long axis): 25–40 μm . Most specimens are indeterminable to species level. Microphytoplankton fossils show low abundance and diversity, predominantly preserved in black to dark brown color. Identified taxa include *Leiosphaeridia* sp. (Figure 6A,N,O), *Visbysphaera microspinosa* (Figure 6B), and subordinate multicellular sporangial fragments (Figure 6C). Palynomorph concentration averages 966 pieces/25 g (variation curve shown in Figure 11).

In this interval, AOM content exhibits an abrupt upward-increasing trend (Figure 11). It primarily occurs as flocculent opaque material with minor TOM, constituting the primary organic facies, averaging 7,514,966.5 pieces/25 g. SOM appears as black or brown, well-defined blocks (80–300 μm long) with good preservation. Distinct porous structures are observable (pore diameters: 0.8–2 μm), interpreted as macroalgal debris and the organic inner lining of sponge spicule (Figure 9B), averaging 8939 pieces/25 g.

(2) Interval 2 (samples SLJ-06 to SLJ-12): Designated as the *Baltisphaeridium* Zone.

This interval corresponds to lithologic Beds 4–8, dominated by silty shale and siltstone with decreasing clay content. The fossil abundance of phytoplankton in this interval shows no significant difference from those in interval 1. A total of five genera and four species were identified, primarily featuring *Baltisphaeridium* sp., with common occurrences of *Dictyosphaera delicata* (Figure 6E), *Leiosphaeridia* sp. (Figure 6F), *Arctacellularia ellipsoidea* (Figure 6H), *Pseudozonosphaera densa* (Figure 6I), *Meghystriospheridium? densum* (Figure 6J), and rare fungal spores. Palynomorph concentration averages 896 pieces/25 g of sediment (variation curve shown in Figure 11).

In this interval, AOM content exhibits a second low-to-high upward-increasing cycle (Figure 11). It is dominated by flocculent and granular opaque material with minor TOM, showing no significant change in average concentration at 4,605,809.6 pieces/25 g. The SOM assemblage in this interval is characterized by abundant macroalgae fragments and animal-derived fragments, including light brown porous fragments (Figure 8D), filamentous and granular fragments (Figure 8E), brown rod-shaped OM fragment (Figure 8F), cylindrical OM fragments (Figure 8N), and so forth (Figure 8). SOM content displays no marked variations, maintaining an average of 15,932 pieces/25 g.

(3) Interval 3 (samples SLJ-15 to SLJ-20): Designated as the *Shuiyousphaeridium* Zone.

This interval corresponds to lithologic Beds 9 to most of Bed 10, excluding the top part, dominated by silty carbonaceous mudstone with upward-increasing clay content. Microphytoplankton fossil diversity and abundance show a moderate increase compared to interval 2. A total of three genera and two species were identified, primarily featuring *Shuiyousphaeridium* sp., with common occurrences of *Acrosphaeridium sensum*, *Shuiyousphaeridium macroreticulatum*, and *Tetrahedraletes medinensis* (Figure 6M). Palynomorph concentration averages 1154 pieces/25 g of sediment (variation curve shown in Figure 11).

In this interval, AOM is dominated by flocculent and granular opaque material with minor TOM, showing an increase in average concentration at 10,824,266.67 pieces/25 g. This interval contains a low amount of animal-derived SOM, mostly composed of sponge spicule linings with minor amounts of brown biostructured membranous sheets. SOM decreased to an average of 9955 pieces/25 g (variation curve shown in Figure 11).

5. Discussion

5.1. Vertical Distribution of Organic-Rich Deposits in the Renheqiao Fm

The exploration and development of Upper Ordovician to Lower Silurian hydrocarbon source rocks have achieved significant success globally. Notably, the geological characteristics and research methodologies of shale gas in the Yangtze region have become exemplary models in China, providing valuable references for shale gas evaluation in other areas [35,44,45]. The Baoshan Block, situated on the southeastern margin of the Tibetan Plateau between the Gaoligong and Chongshan shear zones, shares the same Palaeo-Tethyan tectonic system as the southern Sichuan region (Yangtze Platform). Under the Palaeo-Tethyan Ocean tectonic framework, the Baoshan and Yangtze blocks exhibit similar tectonic-sedimentary evolutionary processes [46]. During the 480–380 Ma period, blocks such as South China, Sino-Indian, Songpan, and Qaidam continuously drifted northward. As the Palaeo-Tethyan Ocean opened, the Baoshan Block was briefly adjacent to the South China Block, leading to the contemporaneous deposition of similar organic-rich shales [23,47]. Graptolite biozone correlation confirms that the Late Ordovician to Early Silurian Renheqiao Fm. in the Baoshan Block is contemporaneous with the Longmaxi Fm. in southern Sichuan, with the R1–R9 graptolite zones of the Renheqiao Fm. being isochronously correlated to the LM1–LM9 zones of the Longmaxi Fm. (Figure 1; [34]).

Influenced by global sea-level fluctuations, the Yangtze region experienced an initial fall followed by a rise in sea level during the Katian–Aeronian, leading to the deposition of the graptolitic shale facies of the Wufeng Fm., the shell limestone facies of the Guanyinqiao Bed, and the graptolitic shale facies of the Longmaxi Fm. [48]. The Baoshan area underwent a similar sea-level fluctuation pattern during the Katian–Aeronian, sequentially depositing the calcareous mudstone facies of the Pupiao Fm., a palaeo-weathering crust, and the graptolitic shale facies of the Renheqiao Fm. During the Katian, the Pupiao Fm. was deposited in a relatively shallow-water environment, characterized by mudstones containing abundant calcareous nodules. Subsequent sea-level fall led to subaerial exposure, and the development of a weathering and denudation crust with associated stratigraphic hiatus. By the middle to upper Hirnantian (i.e., the R1 Zone), the area was re-submerged, depositing graptolitic mudstone facies under rapidly deepening marine conditions. During the Rhuddanian, the graptolitic shale facies of the Renheqiao Fm. developed, accompanied by substantial OM deposition that formed the material basis for hydrocarbon source rocks [49,50]. Therefore, to further understand the spatiotemporal distribution and OM enrichment characteristics of the organic-rich black mudstones/shale in the Renheqiao Fm. within the study area, comparisons were made with well-studied equivalent strata from the periphery of the Sichuan Basin in the Yangtze region and the Yongshan area in Yunnan (Table 2).

Previous studies indicate that the organic-rich shales of the Renheqiao Fm. in the Baoshan area are generally within the mature to post-mature gas-generation window [49–52]. Due to the absence of vitrinite derived from higher plants in Lower Paleozoic sedimentary rocks, graptolite reflectance measurements conducted across the sequences in the study area suggest that the bitumen in the Renheqiao Fm. samples likely originates primarily from graptolites or organic sources with similar structures, exhibiting comparable maturity characteristics. Therefore, to accurately determine the maturity level while accounting for some degree of weathering in the samples, graptolite reflectance—being well-defined in ori-

gin and showing good convergence—was selected as the reference parameter for maturity assessment [53]. Measurements reveal no significant vertical variation in maturity across the four sequences in the study area. Laterally, the highest random graptolite reflectance (GRo) is observed in the Shanglongjing core, reaching up to 1.86%, while the lowest value is recorded in the Chadi section, at only 1.16%. The EqVRo follows a distribution trend consistent with the GRo values (Table 1). Graptolite reflectance values from outcrop samples are lower than those obtained from the two borehole cores, likely due to varying degrees of weathering in the outcrop samples. In contrast, the borehole cores provided a larger number of samples, enabling more measurement points under microscopic examination [2], and generally contained better-preserved graptolites. The random GRo values measured from individual samples predominantly followed a normal distribution, demonstrating robust statistical significance. For example, in the Shanglongjing core, GRo values are 1.86% on average [2]. Therefore, assuming the thermal maturity is comparable between the outcrop and core samples, the GRo data from the Shanglongjing and Changputang wells are highly reliable indicators of OM thermal maturity, though inherent maturity differences between the selected outcrops and the two boreholes cannot be entirely ruled out. Before proceeding to the stratigraphic distribution of organic-rich intervals, it is necessary to consider the potential impact of the methodological constraints outlined in Section 3.2 on our thermal maturity assessment. First, the empirical conversion from GRo to EqVRo [37] may introduce some uncertainty, particularly at the high-maturity end of the spectrum. However, the consistency between our GRo measurements and published data from the same region [2] suggests that any systematic bias is likely minor and does not affect the relative maturity ranking among the studied sections. Second, the slightly lower GRo values obtained from the Chadi and Banpo outcrop sections compared to the borehole cores are consistent with the expected effect of surficial weathering. Crucially, the maturity trend among the four sequences—with Shanglongjing > Changputang > Banpo > Chadi in terms of both GRo and EqVRo—is coherent and geologically plausible, regardless of the absolute values. Therefore, the conclusion that the Renheqiao Formation has reached high to post-maturity, comparable to the Longmaxi Formation in the Yangtze region, remains robust.

Regarding the favorable depositional period of organic-rich shales, previous studies indicate that high-TOC intervals in the Fuling JY-1 and Changning N211 wells of the Yangtze region are predominantly confined to three graptolite biozones (LM2–LM4) within the lower Rhuddanian of the early Silurian [35]. Petrological and organic geochemical analyses further confirm that the corresponding black shales in these intervals represent significant hydrocarbon-producing zones [54–56]. However, the favorable depositional period varies across the Yangtze region, with the Longmaxi Fm. terminating at different levels ranging from LM7 to LM9 biozones. Consequently, the upper boundary of the black shales is diachronous. In some areas, the most prospective intervals are predominantly distributed from the middle-upper Wufeng Fm. to the lower Longmaxi Fm., corresponding to the WF2–LM6 biozones, with a composite thickness of approximately 66.25 m [10,35,45,57].

The TOC% content from the four sequences in the study area generally exhibits the following characteristics: Although the four sequences show significant differences in TOC% content, in the order of Shanglongjing > Chadi > Banpo > Changputang, the favorable intervals display relatively consistent depositional timing distributions. In the Chadi section, the R1–R6 zones all show high TOC%, representing favorable intervals; thus, Beds 2 to 10, with a total thickness of 15.7 m, can be considered as high OM content zones. In the Banpo section, Beds 1–2 (middle R6 Zone) exhibit relatively low TOC%, while the remaining intervals constitute favorable depositional zones for organic-rich mudstones, with a cumulative thickness of 42 m (Figure 4). Both the Changputang and Shanglongjing boreholes show lower TOC% and AOM content in the middle R6 Zone, which does not

belong to the favorable intervals, while the remaining zones are prospective, with 42.5 m in Changputang and a cumulative 32 m in Shanglongjing. Therefore, the favorable intervals in the Renheqiao Fm. can be defined as the lower R1–R6 zones and the upper R6–R9 zones, with a total thickness of approximately 74–84.5 m (Figure 11), which is not inferior to the favorable depositional areas in the Yangtze region.

Table 2. Graptolite biozones, thickness, sedimentary rate, and TOC% comparison between the Chadi and Banpo sections, Xindi 2, and Jiaoye 1 boreholes. (Biozone durations are calibrated to the Geologic Time Scale 2012 [58]; sedimentation rate ranges are calculated assuming a conservative $\pm 10\%$ uncertainty in biozone duration).

System	Series	Stage	Fossil Zone	Duration of Deposition ($\pm 10\%$ Ma)	Chadi Section (This Study)			Banpo Section (This Study)			Xindi 2 Borehole [35]			Jiaoye 1 Borehole [10,59]		
					Thickness (m)	Deposition Rate (m/Ma)	TOC (%)	Thickness (m)	Deposition Rate (m/Ma)	TOC (%)	Thickness (m)	Deposition Rate (m/Ma)	TOC (%)	Thickness (m)	Deposition Rate (m/Ma)	TOC (%)
Silurian	Llandovery	Telychian	R9 (LM9)	0.36				>8.8 (Top unexposed)	>24.44 (22.22–27.16)	2.33						
			R8 (LM8)	0.27				2.3	8.52 (7.74–9.47)	2.65	52.99	196.26	0.74	>44.19	>163.67	1.43
		Aeronian	R7 (LM7)	0.45				9.4	20.88 (18.99–23.21)	1.78	40.65	90.33	1.31	4.03	8.96	2.40
			R6 (LM6)	1.56	>7.25 (Top unexposed)	>4.64	2.29	>33.5 (Base unexposed)	>21.51 (19.52–23.86)	2.33	36.53	23.42	2.76	19.21	12.31	1.99
			R5 (LM5)	0.8	3.48	4.35 (3.95–4.83)	2.04				2.10	2.62	3.94	23.15	28.94	2.59
		Ruddanian	R4 (LM4)	0.9	1.87	2.07 (1.89–2.31)	4.46				9.20	10.22	5.85	13.69	15.21	3.66
			R3 (LM3)	0.93	0.79	0.84 (0.77–0.94)	6.02									
			R2 (LM2)	0.43	0.85	1.97 (1.80–2.20)	2.82				12.40	9.12	3.79	3.49	2.57	4.67
Ordovician	Upper Ordovician	Hirnantian	R1 (LM1)	0.6	0.85	1.42 (1.29–1.57)	2.33				1.07	1.78	6.16	4.34	7.23	3.22
			wf4	0.73												

5.2. Relationship Between Sedimentation Rate and Depositional Environment of the Renheqiao Fm

To further analyze the relationship between sedimentation rate and depositional environment in the Renheqiao Fm. within the study area, sedimentation rates were calculated based on graptolite biozone age data calibrated to the Geologic Time Scale 2012 (GTS2012) [58] and Sedimentation Rate (m/Ma) = Formation Thickness (m)/Biozone Duration (Ma). These calculations involve two key assumptions: (1) that compaction has not significantly altered the original thickness, and (2) that the mean age durations of the graptolite biozones are accurate. Uncertainties associated with these assumptions imply that the calculated rates are best interpreted as generalized estimates. According to GTS2012 ([58] Table 1), the 95% confidence uncertainty for Silurian stage boundaries ranges from ± 1.1 to ± 1.5 Ma. Given that our graptolite biozones are subdivisions of these stages, a conservative $\pm 10\%$ uncertainty in biozone duration is well within the range of uncertainty acknowledged by the international time scale community. The acknowledgment and quantification of uncertainty in geological time scaling and resource assessment are widely recognized as essential practices in unconventional hydrocarbon studies (e.g., [60]). Our approach (using a conservative $\pm 10\%$ uncertainty in biozone duration to calculate sedimentation rate ranges) is fully consistent with this principle. These rates were compared with data from the Xindi 2 and Jiaoye 1 wells in the Yangtze region (Table 2).

Since the R1–R5 biozones are only exposed in the Chadi section, data from this section were used for calculations in these intervals. For the R6–R9 biozones, the Banpo section was selected for sedimentation rate calculations due to its abundant graptolite preservation, de-

tailed research, and high reliability of stratigraphic thickness, as the three sequences (Banpo, Changputang, and Shanglongjing) show similar thickness variations in each graptolite biozone and consistent TOC% and AOM trends. Although TOC% content varies among the four study areas, the general variation patterns remain consistent. Thus, the Banpo section, which shows closer characteristics to the two Yangtze region wells, was selected as representative for discussing the impact of sedimentation rate on OM enrichment, while also considering data from the Changputang and Shanglongjing sequences.

The results show that the cumulative thickness of the R1–R4 graptolite biozones in the Chadi section is relatively small, measuring only 2.49 m, which aligns with previous descriptions of stratigraphic thickness variations in the Baoshan area [32,51]. In terms of sedimentation rate, the mean value for the R1–R4 biozones in the Chadi section is 1.41 m/Ma, which is 6.9–7.7 times lower than that of the Xindi-2 and Jiaoye-1 wells in the Yangtze region. However, the average TOC% content reaches 4.27%, comparable to the mean TOC% of 4.56% in the LM1–LM3 biozones of the Xindi-2 and Jiaoye-1 wells [10,59]. Analysis suggests that, during this period, the Yangtze region was significantly influenced by marine regression, leading to a substantial increase in sedimentation rate, greater stratigraphic thickness, and OM enrichment. In contrast, the Baoshan area experienced a more gradual marine regression, resulting in relatively thinner strata but conditions highly conducive to OM enrichment and preservation.

In the R6 Zone, the Banpo section, Changputang borehole, and Shanglongjing borehole all span substantial stratigraphic thicknesses of approximately 33.5 m, 44.7 m, and 42.7 m, respectively, reflecting the relatively stable variation characteristics of the Baoshan Block. This is consistent with the 36.53 m thickness of the LM6 Zone in the Xindi-2 well from the Yangtze region. During this stage, the sedimentation rate in the Banpo section exceeds 21.51 m/Ma, showing a magnitude and degree of influence comparable to the 23.42 m/Ma rate in the Xindi-2 well, both characteristic of high sedimentation rates. Despite clear regression influences, TOC% values at both locations remain at averages of 2.29% and 2.76%, without significant decline under the dilutive effect of high sedimentation rates, demonstrating acceptable OM enrichment. Therefore, in the Baoshan area, the R5 Zone represents only the initial phase of marine regression, whereas, in the Yangtze region, the Jiaoye-1 well experienced concentrated regression effects during the LM5 stage and the Xindi-2 well showed more pronounced regression influence by the LM6 stage.

Starting from the R7 Zone, the thickness of this zone across all studied locations in the Baoshan area is relatively thin, with an average of 5.7 m, a trend consistent with the LM7 Zone in the Jiaoye-1 well. In the Banpo section, the R7 Zone exhibits a sedimentation rate of 20.88 m/Ma, remaining high and indicating a continued regression process. Overall, a transgression occurred across the Baoshan area after the R7 Zone, though with minor local variations. This is most evident in the R8 Zone of the Banpo section, which reflects a sediment-starved state during the maximum flooding stability period, characterized by minimal thickness and slow deposition over 0.27 Ma. During this interval, TOC% shows some recovery. In contrast, the Changputang and Shanglongjing cores recorded this process earlier, within the R7 Zone.

Unlike the LM7–LM8 zones in the Jiaoye-1 well in the Yangtze region, which were influenced by maximum flooding [35], the Baoshan area experienced a later regression during the R9 Zone. Notably, TOC% did not decrease significantly despite increased sedimentation rates, indicating sustained OM enrichment. During the regression cycle, changes in the depositional environment and the shift from reducing to oxidizing conditions affected nearshore areas earlier. This distinct pattern, characterized by comparable or greater cumulative thicknesses of organic-rich intervals despite differing sedimentation rates, is consistent with a delayed response of the Baoshan Block to regional sea-level

fluctuations due to its more distal paleogeographic setting on the Sibumasu Block [61–64]. This pattern of sustained organic enrichment in a distal, slope-related setting is consistent with the “continuous accumulation” model for unconventional hydrocarbon systems described by Kokkinos et al. [60], who emphasized the importance of basin-center and basin-slope settings for long-term organic matter preservation.

5.3. Characteristics of Hydrocarbon-Generating Organism Assemblages and Their Correspondence with OM Distribution

The investigated sequences exhibit strong consistency in TOC%, AOM content, and distribution characteristics of organic-walled fossils, with minimal variation in the thickness of each fossil zone. Based on these characteristics, the hydrocarbon-generating organisms and OM distribution in the Renheqiao Fm. can be divided into three stages (Figure 12).

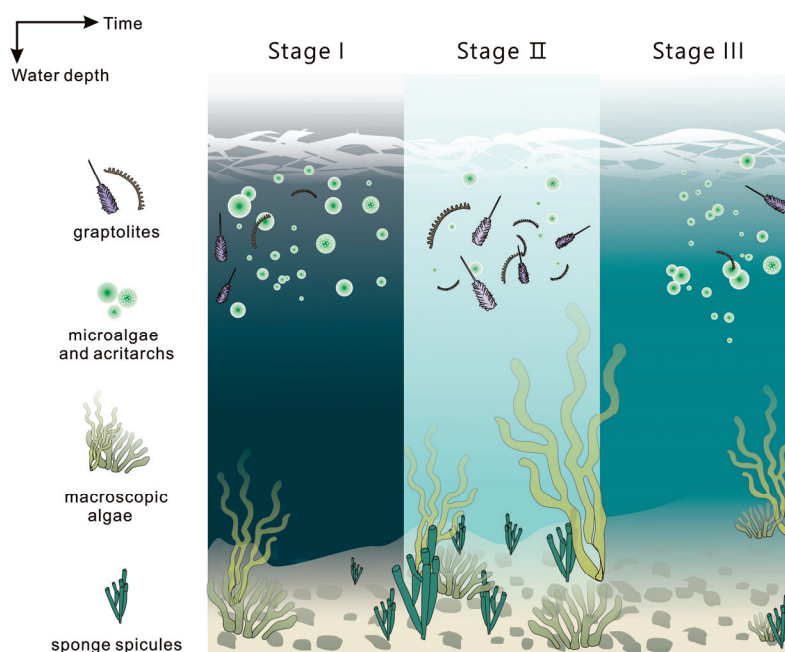


Figure 12. A schematic diagram showing the three-stage hydrocarbon-generating organism assemblages of the Renheqiao Fm. (legend indicates types, not actual sizes).

Stage I spans the R5 Zone to the lower R6 Zone, with an average thickness of 11.9 m across the four sequences. Including the 5.2 m thickness from the R1–R4 zones in the Chadi section, the total thickness reaches 17.1 m. This stage corresponds to the *Leiosphaeridia* Zone identified in the Changputang and Shanglongjing boreholes, characterized by high TOC%, high palynomorph content, and high AOM, indicating organic-rich conditions. The hydrocarbon-generating organisms in this stage are primarily microalgae and acritarchs, with some macroscopic algae and minor sponge spicules (Figure 12). Graptolite content shows an increasing trend, contrasting with the declining TOC% curve (Figure 4). Furthermore, the relatively low sedimentation rate during this stage favored OM accumulation.

Stage II corresponds to the middle R6 Zone, with an average thickness of 17.9 m across the four sequences. This interval is equivalent to the *Protosphaeridium-Baltisphaeridium* Assemblage Zone in the Changputang borehole and the *Baltisphaeridium* Zone in the Shanglongjing borehole. Decreases in TOC%, palynomorph content, and AOM are observed, indicating poor OM enrichment. The composition of hydrocarbon-generating organisms during this stage shows a notable increase in macroalgae and animal-derived OM, while microplanktonic algae and acritarchs decrease (Figure 12). Additionally, correlation analysis further confirms the negative relationship between graptolite abundance and TOC%,

with the analysis yielding a moderate negative correlation with a correlation coefficient of $R = -0.54$. This relationship is statistically significant, with a p -value of $p = 0.038$ ($p < 0.05$) (The raw data are provided in the Supplementary File). The quantitative evidence now provides clear and testable support for our interpretation of a negative relationship between graptolite abundance and TOC enrichment. This supports the interpretation that higher graptolite abundances are associated with lower OM enrichment. This association could be explained by graptolites acting as consumers of primary productivity, and by environmental conditions favoring graptolite communities (e.g., better-ventilated water masses) being less favorable for OM preservation.

It is certain that the overall lower TOC% levels in the R6 Zone are influenced by dilution from increasing terrestrial input, as demonstrated in Section 4.2. At the same time, the decline in TOC% during this stage is clearly controlled by changes in palynological OM content and hydrocarbon-generating assemblage. Therefore, it can still be demonstrated that the OM enrichment is affected by the hydrocarbon-generating assemblage, rather than being unidirectionally diluted solely due to the increase in sedimentation rate.

Stage III spans the upper R6 Zone to the R9 Zone, with an average thickness of 27.1 m across the four sequences. This stage corresponds to the *Shuiyousphaeridium* Zone identified in both the Changputang and Shanglongjing boreholes. During this interval, TOC%, palynomorph content, and AOM all increased significantly, indicating excellent OM enrichment. The composition of hydrocarbon-generating organisms in this stage shows an initial marked decline in macroscopic algae, with animal-derived OM limited to minor sponge spicules, while microplanktonic algae and acritarchs become more abundant (Figure 12). Persistently low graptolite content coincides with rising TOC% (Figure 4). Although the overall sedimentation rate during this stage remained high, OM accumulation was not strongly diluted, indicating that depositional conditions remained favorable.

Therefore, the high-quality hydrocarbon-generating organisms in the Renheqiao Fm. are microphytoplankton such as algae and acritarchs, rather than macroscopic algae. Animals exert a negative impact on productivity; for instance, both animal-derived debris and graptolites are associated with reduced productivity, likely due to their role as secondary consumers that deplete primary productivity.

6. Conclusions

The Renheqiao Fm. in the Baoshan region (western Yunnan, China) accumulated on the central Sibumasu Block, a setting that was located farther offshore in the Proto-Tethys Ocean. Understanding such depositional systems in ancient oceanic margins provides a critical analogue for evaluating hydrocarbon potential in modern, similarly situated marine basins away from major terrigenous input. Based on the results, the following conclusions can be drawn:

1. The vertical distribution of organic-rich shales in the Renheqiao Fm. is well-defined, with the thickness and duration of its high-quality intervals effectively comparable to those of the Longmaxi Fm. in the Yangtze region. The depositional timing of favorable intervals is highly consistent: they are primarily concentrated in the lower R1–R6 and upper R6–R9 graptolite biozones, with a cumulative thickness of 74–84.5 m, which is not less than that of the main intervals in the Yangtze region.
2. Graptolite reflectance values (1.16–1.86%) and equivalent vitrinite reflectance values (1.23–1.92%) from the Renheqiao Fm. indicate a high to post-maturity stage of thermal evolution. This maturity range is broadly comparable to that of the productive Longmaxi Formation in the Yangtze region, suggesting that the formation has entered the late hydrocarbon generation window and holds significant potential for shale gas.

3. The Renheqiao Fm. exhibits a sedimentary pattern characterized by an apparent delayed response to regional regressive trends yet sustained organic enrichment, which differs in detail from the sequences of the Yangtze Plate. This distinctive pattern is best explained by its more distal tectonic setting on the Sibumasu Block, which likely buffered it from the immediate effects of marine regression. We interpret that this setting was conducive to prolonged and enhanced OM accumulation.

4. The hydrocarbon-generating organism assemblages in the Renheqiao Fm. can be divided into three stages: The first stage (lower R1–R6 zones) is dominated by micro phytoplankton and acritarchs, corresponding to high TOC% and AOM content, representing the most favorable hydrocarbon-generating assemblage; the second stage (middle R6 Zone) shows an increase in macro algae and animal-derived debris, a decrease in micro phytoplankton, and a significant reduction in TOC%; the third stage (upper R6–R9) marks a recovery of micro phytoplankton and renewed OM enrichment. These assemblages indicate that primary producers (microphytoplankton/acritarchs) are associated with high-quality hydrocarbon generation potential. In contrast, secondary consumers (e.g., graptolites, sponges) are linked to conditions less favorable for OM preservation and/or may have played an inhibitory role in net accumulation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse14050436/s1>.

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Abbreviations

The following abbreviations are used in this manuscript:

Fm.	Formation
TOC	total organic carbon
OM	organic matter
AOM	amorphous organic matter
SOM	structured organic matter
TOM	transparent amorphous organic matter
GRO	graptolite random reflectance
EqVRO	equivalent vitrinite reflectance

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Article

Strike-Slip Activity of the Tinjar–West Baram Fault in the Southern South China Sea: Implications for Sedimentation in the Zengmu Basin and Hydrocarbon System

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Abstract

The Tinjar–West Baram Fault in the southern South China Sea is a major NW-trending strike-slip fault that has remained tectonically active since the Oligocene. It forms a key structural boundary between the Zengmu, Beikang, and Nansha Trough basins. Multi-phase strike-slip movements have strongly controlled sediment provenance dispersal pathways, and reservoir development in the Zengmu Basin, yet the sedimentary response to these tectonic processes remains poorly understood. This study integrates 2D seismic profiles to analyze the fault geometry, kinematics, and impact on deep-water sedimentary systems. Results indicate that Oligocene right-lateral motion directed sediment supply from the southwest, mainly sourced from Kalimantan, forming fluvial–deltaic systems with depocenters in the southern basin. Since the Late Miocene, a transition to left-lateral motion reoriented sediment provenance toward the southeast, leading to delta-front complexes and northward migration of depocenters. Strike-slip activity deformation enhanced rock fragmentation and sediment supply, producing fan delta, fluvial, and shallow lacustrine facies near the fault. Associated uplift and subsidence induced relative sea-level fluctuations, resulting in alternating transgressive–regressive sequences. From the Late Eocene to Miocene, the basin evolved from a land–sea transitional system to a deltaic–carbonate complex controlled by the paleo-Sunda River. During the Pliocene–Quaternary, sedimentation was dominated by shallow-marine shelf and semi-deep-marine deposits. Fault-related fracturing significantly enhanced porosity and permeability, creating favorable conditions for hydrocarbon migration and entrapment in both sandstone and carbonate reservoirs. These findings demonstrate a strong coupling between strike-slip fault activity and sedimentary system evolution, providing important insights into sedimentary processes and hydrocarbon potential in strike-slip fault-bounded basins globally.

Keywords: sedimentary control; strike-slip activity; Tinjar–West Baram Fault Zone; Zengmu Basin; southern South China Sea

1. Introduction

The South China Sea lies at the convergence of the Eurasian, Pacific, and Indo-Australian plates, making it the largest marginal sea in the western Pacific. Its tectonic evolution reflects the combined influence of the Tethyan and the Pacific tectonic domains [1,2], resulting in highly complex tectonic activity. Interactions among the Indochina Block, Nansha Block, and Sarawak-Sulu accretionary belt led the development of several medium- to large-scale sedimentary basins along the South China Sea margins. Although numerous

evolutionary models have been proposed [3–5], the role of the Tinjar–West Baram Fault, a major NW-trending strike-slip fault in the southern South China Sea, remains critical for understanding sedimentary patterns and hydrocarbon accumulation in the Zengmu Basin. Active since the Oligocene, the fault, which experienced right-lateral motion initially, shifted to left-lateral motion during the Late Miocene, and reverted to right-lateral motion from the Pleistocene to the present [6–9]. This complex kinematic evolution has strongly controlled basin architecture, sediment dispersal, and reservoir development.

Strike-slip activity induced differential uplift and subsidence, shaping basin paleotopography and sediment supply. Uplifted fault adjacent areas generated steep topographic gradients that enhanced erosion and supplied short-transport clastics, forming alluvial fan and fan deltas, whereas gentler slopes favored distal fluvial-deltaic systems with improved sediment sorting. During the early right-lateral phase (Oligocene–Miocene), coarse-grained deposits accumulated near steep slopes, while during the Late Miocene left-lateral phase, the depocenters migrated northward and fine-grained lacustrine or deep-marine sediments became dominant. Fault reaction also promoted the formation of structural traps through alternating extensional and compressional stress regimes, generating fault blocks and folds [10]. Secondary fault networks enhanced reservoirs connectivity, while fault zones served as vertical migration pathways for hydrocarbon accumulation in shallow traps. Changes in strike-slip direction further controlled depocenter migration. Since the Late Miocene, reversal from left-lateral to right-lateral motion shifted the sedimentary center from south to north, altering facies distribution, sediment thickness, and lithofacies transitions. These processes also regulated the spatial distribution of high-quality reservoirs through the development of structural slope breaks [11]. Despite these advances, sedimentary reservoir development under the multi-phase strike-slip regime of the Tinjar–West Baram Fault remains insufficiently understood, particularly regarding hydrocarbon accumulation patterns on either side of the fault. The Zengmu Basin and the adjacent Brunei–Sabah Basin, contain thick Neogene successions [12–14], making the fault system a key control on regional petroleum systems. Consequently, clarifying the sedimentary characteristics and hydrocarbon significance of the Tinjar–West Baram Fault in the Zengmu Basin remains a major research challenge in South China Sea studies.

2. Geological Background

The Tinjar–West Baram Fault Zone (T–WBFZ) is a major NW-trending strike-slip fault system in the southern South China Sea. It forms the structural boundary between the Nansha and Zengmu blocks and extends from the Tinjar River regions of Kalimantan northeastward into the offshore West Baram Fault. The T–WBFZ defines the southwestern margin of the South China Sea Basin and terminates the extension of the Nansha Trough. Structurally, it exerts strong control on basin development and sedimentation, as evidenced by thick Neogene accumulations in the Zengmu and Brunei basins formed through tilting and differential subsidence along the fault. This structural framework has also played a key role in hydrocarbon migration and accumulation [3,15]. The evolution of the Zengmu Basin reflects complex tectonic interactions related to the subduction and closure of the proto-South China Sea, followed by opening of the present South China Sea [16,17]. Throughout these processes, the Tinjar–West Baram Fault acted as a fundamental structural boundary controlling basin initiation, sediment infill, and hydrocarbon system development [18]. Since the Cenozoic, basin evolution can be divided into three stages: (1) Late Cretaceous–Early Eocene foreland basin subsidence; (2) Oligocene–Early Miocene strike-slip reactivation; and (3) Middle Miocene–Quaternary regional subsidence. Geographically, the Zengmu Basin is located in the southwestern offshore Nansha region, east of Natuna Island, west of the Nansha Trough, south of the Wan’an Shoal–Beikang

Slope, and north of the Beikang Basin. The basin is characterized by intense faulting accompanied by Cenozoic magmatic intrusions and volcanic activity [18]. Based on fossil assemblages, lithology, and seismic interpretation, a Cenozoic sequence stratigraphic framework has been established [19]. Seismic data identify five major unconformities (T2, T3, T4, T5, and Tg), defining five seismic sequences: T5–Tg (Lower-Middle Eocene), T4–T5 (Upper Eocene–Lower Oligocene), T4–T3 (Oligocene–Miocene), T3–T2 (Pliocene), and T2 and younger (Quaternary). Tectonic style, sedimentary architecture, and basement composition vary across the basin. The southern sector is dominated by deformed Paleogene strata and exposed basement, whereas the northern basement shows affinities with other Nansha basins. Structurally, the Zengmu Basin is subdivided into eight secondary units: Suokang Depression, Lanai Uplift, Tatau Depression, West Baram Uplift, East Baram Depression, South Kang Plateau, Kangxi Depression, and the Western Slope, with the Kangxi Depression forming the principal depocenter (Figure 1).

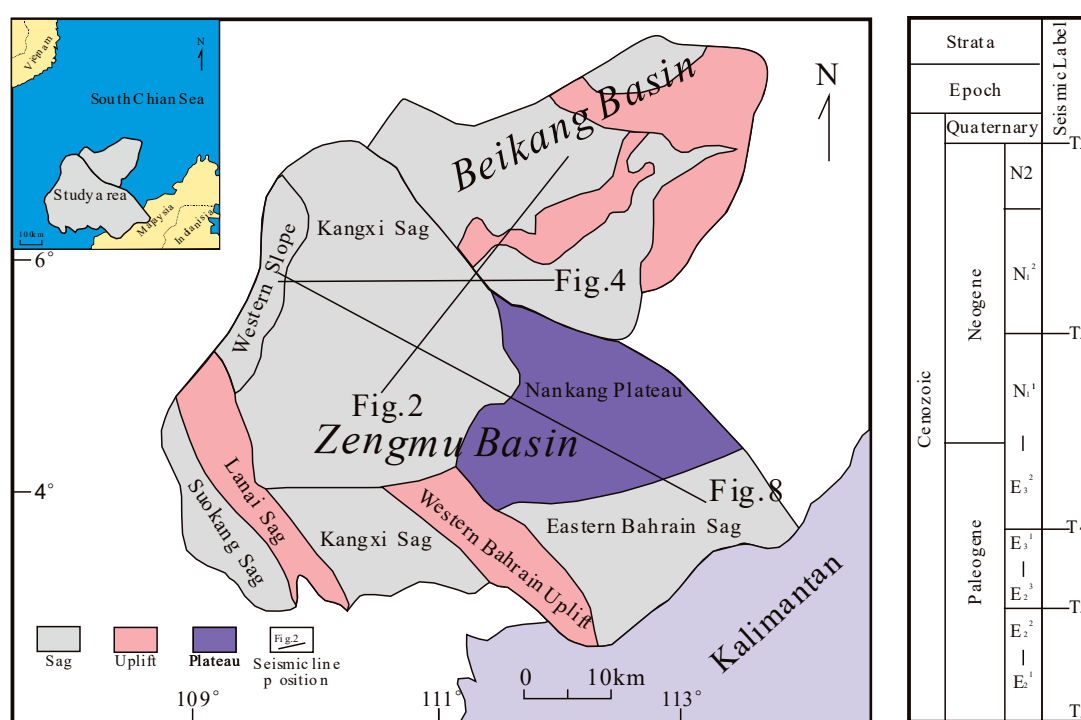


Figure 1. Tectonic and stratigraphic map of Zengmu-Beikang Basin.

The basin contains well-developed Eocene–Oligocene, Neogene, and Quaternary successions, with total sediment thickness ranging from 2000 to 11,000 m. Middle Miocene and younger deposits are typically 2000–4000 m thick, thickening northward and thinning southward [20–22]. The Zengmu Basin petroleum system is characterized by Oligocene–Miocene coal-bearing strata and marine mudstones as source rocks, sandstones and carbonates as reservoirs, and mudstones and shales as seals. Sandstone reservoirs exhibit average porosities of 15–20% and permeabilities of 50–150 mD, whereas carbonate reservoirs show superior properties, with porosities of 25–30% and permeability of 300–500 mD. Hydrocarbon accumulation is controlled by both structural and depositional factors, producing diverse trap types and a characteristic “south-oil, north-gas” distribution pattern [23–25].

3. Data Sources and Methods

3.1. Multi-Channel Seismic Data Acquisition

High-resolution multi-channel seismic data were acquired by the Marine Geological 16 survey vessel of the Guangzhou Marine Geological Survey Bureau. Acquisition param-

eters included 96 receiver channels with a 25 m spacing, 24-fold coverage, a 50 m shot interval, 250 m minimum offset, 2 ms sampling rate and 7 s record length. The air-gun source had a total volume of 2821 in³, an array length of 2625 m, a source depth of 8 m, and a streamer depth of 12 m. The survey grid spacing was approximately 40 km × 80 km.

3.2. Seismic Data Reprocessing

Seismic data were reprocessed using advanced workflows to enhance signal quality and imaging accuracy. Key steps included pre-stack multi-domain noise attenuation, multiple suppression, amplitude compensation, τ -p deconvolution, zero-phase deconvolution, complex velocity modeling in structurally complex zones, and pre-stack time migration using curved-ray algorithms. These procedures significantly improved resolution and signal-to-noise ratio enabling detailed structural and stratigraphic interpretation.

3.3. Seismic Data Interpretation

Seismic interpretation was performed using Schlumberger's GeoFrame 4.5 software platform, where an integrated interpretation database was established for horizon picking, fault mapping, and seismic-stratigraphic analysis.

4. Results and Discussion

4.1. Characteristics of the Tinjar–West Baram Fault

Seismic profiles show that the Tinjar–West Baram Fault Zone (T-WBFZ) displays classic strike-slip fault characteristics, with pronounced along-strike variations in tilting intensity that produce significant stratigraphic thickness contrasts across the fault. A prominent high-angle negative flower structure is observed, with the fault penetrating, basement rocks and vertically cutting through Cenozoic strata, forming a deeply rooted fault system. This structural architecture reflects multi-phase strike-slip activity; early right-lateral motion promoted rift basin development, whereas subsequent reactivation led to stratal tilting and depocenter migration. Marked stratigraphic contrasts across the fault include variations in thickness, orientation, and seismic facies. Fault activity also produced extensive secondary fault networks, which act, as major hydrocarbon migration pathways and control the distribution of tilted fault blocks, graben-horst structures, and associated sedimentary architectures (Figure 2).

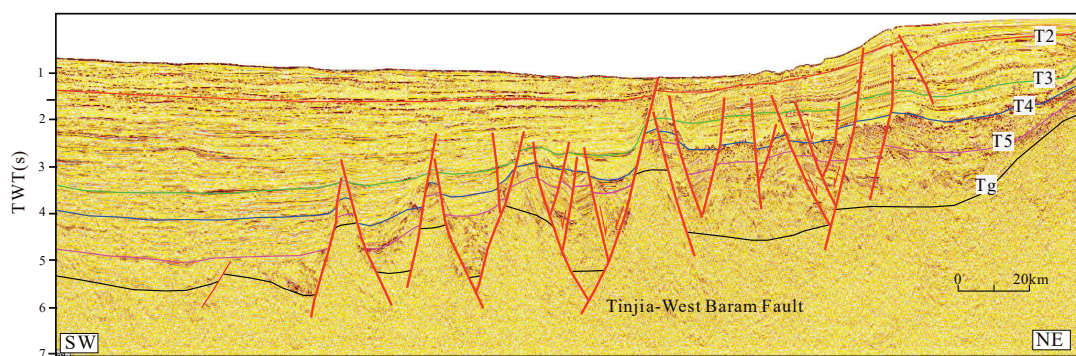


Figure 2. Cross-sectional Characteristics of the Tinjar–West Baram Fault (location shown in Figure 1).

In map view, the T-WBFZ exhibits a chevron-shaped strike-slip pattern, reflecting complex regional plate motions. This fault system controls the development of NW-trending subsidiary faults in the southern basin, which display a characteristic pattern of “northwest convergence and southeast divergence”, arcuate geometries, branching structure, variable fault widths, and evidence of multi-phase deformation, highlighting the dynamic tectonic evolution of the region (Figure 3).

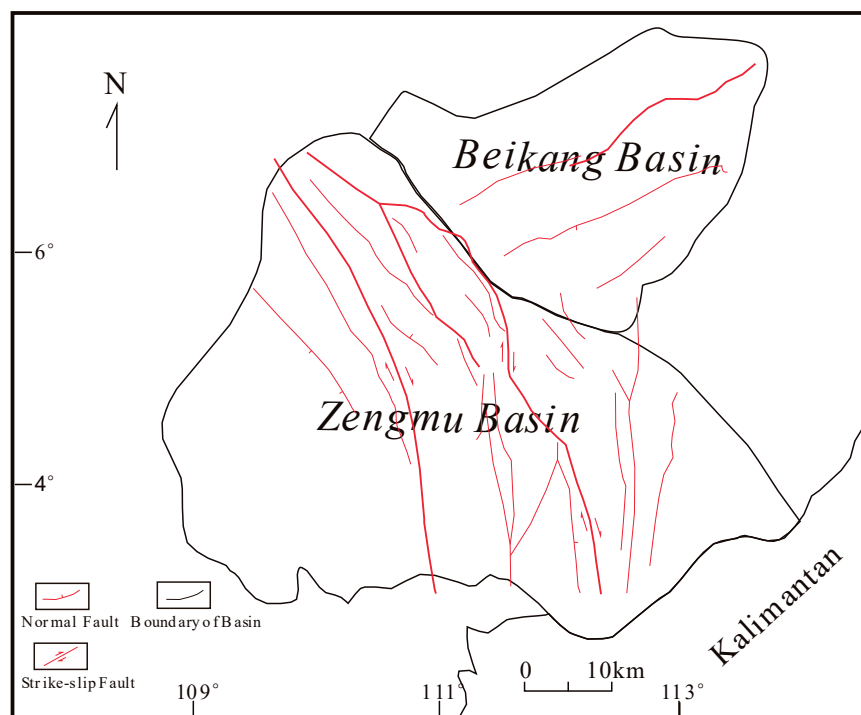


Figure 3. Fault distribution map of the Tg reflection layer.

4.2. Influence of Faulting on Sedimentary Depocenter Migration

Sedimentation and subsidence in the Zengmu Basin are primarily controlled by fault activity, with fault timing and kinematics exerting strong influence on the development and migration of sedimentary depocenters. During the Late Cretaceous Early Eocene, southward subduction of the proto-South China Sea caused basement uplift and the formation of horst–graben structures. From the Late Eocene to Late Oligocene, activation of the Tinjar–West Baram Fault Zone (T-WBTZ) initiated basin subsidence, largely governed by inherited basement faults beginning at ~23.8 Ma. By the end of the Early Miocene (~16 Ma), intensified subsidence in the southern basin established the principal depocenter. Inherited basement faults continued to control stratigraphic architecture, producing alternating zones of uplift and subsidence. During the Middle–Late Miocene (ca. 10.2–5.3 Ma), ongoing fault activity drove northward migration of the sedimentary center, accompanied by rapid sediment accumulation and continued subsidence, while most basin faults gradually became inactive. Since the Quaternary (~1.8 Ma), renewed differential subsidence, clearly imaged in seismic profiles, has further shifted the depocenter northward toward the Beikang Basin. Overall, the Zengmu Basin records a persistent south-to-north migration of sedimentary centers through time.

4.3. Influence of the Faulting on Basin Tectonic Evolution

Late Cretaceous–Eocene: During the late Maastrichtian, the Lucania Block, hosting the Zengmu Basin, was situated in northern Kalimantan. From the Paleocene to early Eocene, southwestward subduction of the proto-South China Sea beneath the Kalimantan Block caused southward drift of the Lucania Block without direct collision. By the late Eocene, continued southward motion resulted in initial collision between the southern margin of the Lucania Block and the Kalimantan accretionary complex. Basin development during this stage was primarily controlled by basement faults, including the Lupal and Bukit Mersing faults, which induced flexural subsidence and localized rifting. Subsidence was concentrated along the subduction margin, with the Nankang Platform, southwest of the Tinjar Fault, acting as the main depocenter.

Oligocene–Early Miocene: During the Oligocene, the Tinjar–West Baram Fault initiated significant strike-slip activity. Under combined compressional and strike-slip deformation, the southern Zengmu Basin became the main depocenter. In the Early Miocene, continued southward subduction of the Nansha Block beneath Sabah impeded further southward movement of the Zengmu Block, while the Tinjar–West Baram Fault exhibited pronounced dextral motion. Intensifying collision between the ucania and Kalimantan blocks led to progressive closure of the proto-South China Sea. Uplift along the southern Lucania margin formed a foreland orogenic belt, transforming regional paleogeography from “high in the north, low in the south” to “high in the south, low in the north.” This uplift supplied abundant sediment to the Zengmu Basin. In the southeastern basin, NE-trending en echelon faults developed under dextral strike-slip control along the Tinjar–West Baram Fault (Figure 4). Associated fault blocks and reef complexes formed structural traps, providing favorable conditions for subsequent hydrocarbon generation and accumulation.

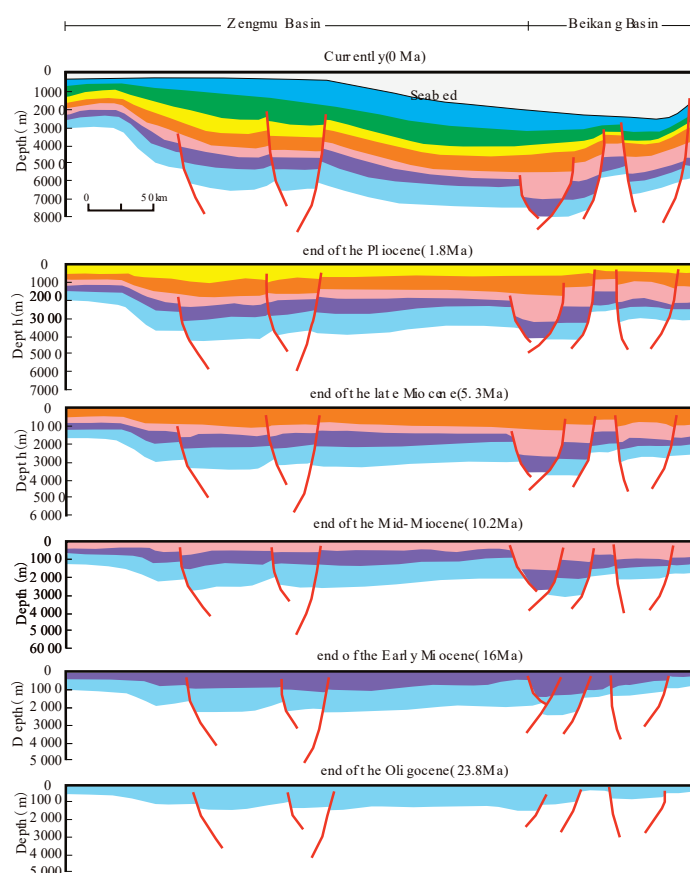


Figure 4. Cenozoic tectonic evolution profile of the Zengmu Basin (modified from [19]) (location shown in Figure 1).

4.4. Characteristics of the Sedimentary Evolution

The Zengmu Basin records a progressive sedimentary evolution closely linked to its tectonic development. Four major stages are recognized: (1) a lacustrine system during the Late Paleocene–Eocene rift stage (Tg–T5); (2) expanded lacustrine deposition during peak rifting in the Oligocene (T5–T4); (3) a deltaic–marine transgressive system during Early Miocene subsidence (T4–T3); and (4) a fully marine transgressive system from the Middle–Late Miocene to the Quaternary (T3–Q). Accordingly, the basin was successively infilled by rift-related lacustrine sediments, transitional deltaic deposits, and ultimately shallow- to semi-deep-marine sediments formed during long-term thermal subsidence (Figures 5–7). During the rift climax stage (T5–T4), rising relative sea level promoted

transitional continental-marine environments, including coastal plains, coastal swamp, shallow-marine, and semi-deep-marine settings. From the sag stage onward (T3 and younger), widespread marine transgression dominated deposition. Sediment supply was primarily derived from the Lalan River Delta to the south, prograding northward and forming extensive coastal-deltaic sequences. Continued sea-level rise shifted sedimentation toward shallow- and semi-deep-marine facies and eventually deep-marine deposits. Controlled by T3 paleogeomorphology and sediment supply variations, extensive subaqueous distributary channels, deep-water fans, and turbidite systems developed in the Beikang Basin, reflecting a mature marine depositional system under sustained thermal subsidence and high accommodation.

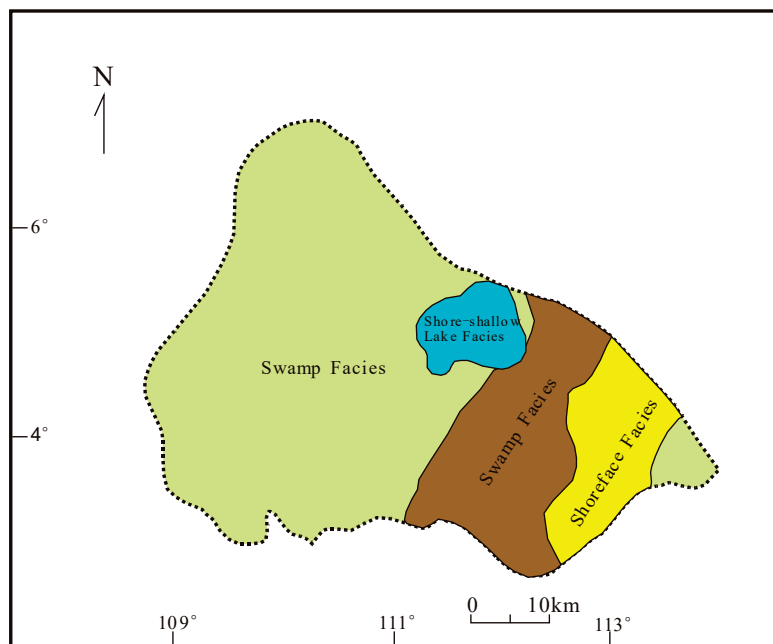


Figure 5. Planar sedimentary facies distribution map of the Zengmu Basin during the rift stage (Tg–T5).

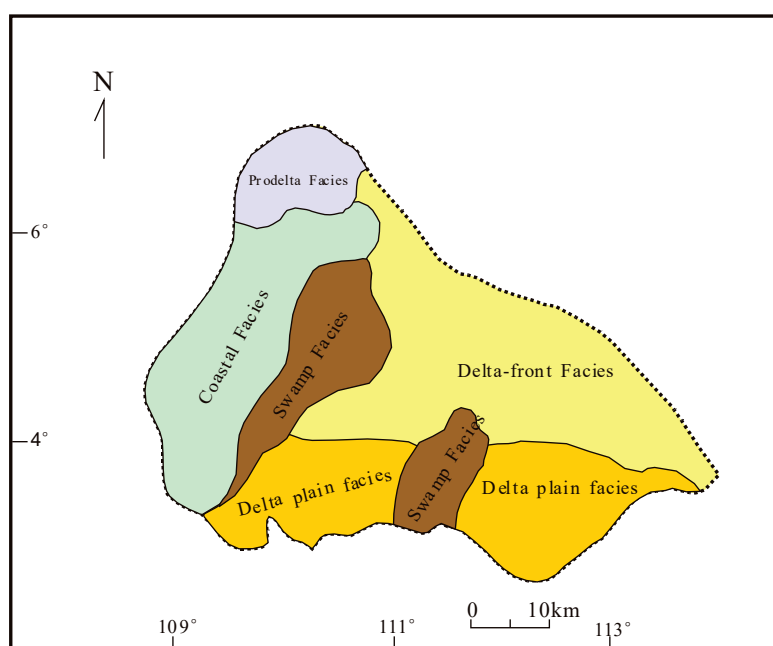


Figure 6. Sedimentary facies map of the early sag stage in the Zengmu Basin (T5–T4).

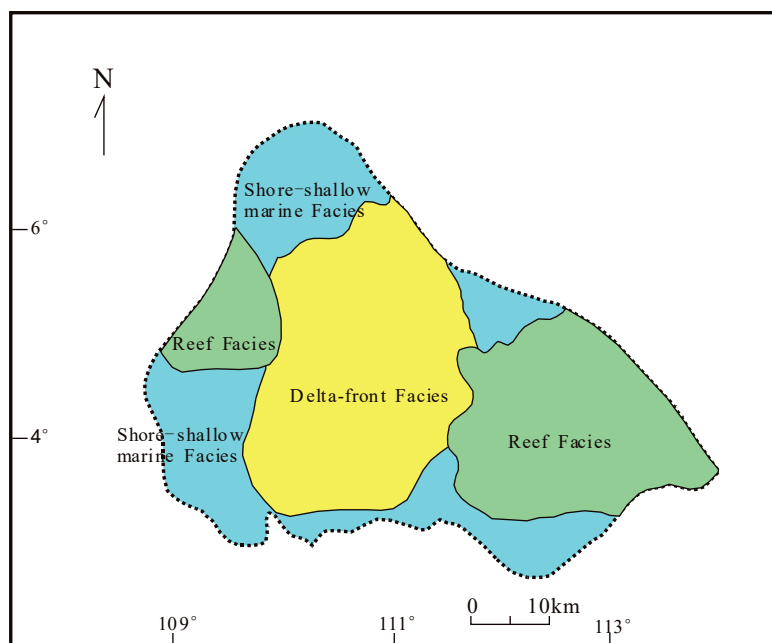


Figure 7. Sedimentary facies map of the sag stage in the Zengmu Basin (T3–Currently).

4.5. Role of Faulting in Hydrocarbon Accumulation

Fault activity has exerted a fundamental control on both Cenozoic tectonic evolution and hydrocarbon generation, migration, and accumulation in the Zengmu Basin. The principal reservoirs comprise Oligocene–Miocene sandstones and Middle–Upper Miocene limestones or reefal carbonates. Clastic reservoirs are primarily distributed in the southern uplift and East Baram Depression, whereas carbonate reservoirs are concentrated on the northern Nankang Platform and western basin slope. From the Eocene to Early Miocene, compressional tectonism related to collision between the southern basin margin and Kalimantan caused significant uplift in the southern basin, favoring the development of a self-sourced, self-reservoired, and self-sealed petroleum systems dominated by deltaic sandstones interbedded with coastal-plain and shallow-marine mudstones. During the Middle Miocene, continued strike-slip activity along the Tinjar–Sabalan Fault Zone promoted the formation of extensive carbonate platforms on the western slope and Nankang Platform, enhancing reservoir potential. Since the Late Miocene, regional thermal subsidence has dominated basin evolution, leading to deposition of thick, laterally continuous shallow- to semi-deep-marine mudstones that act as effective regional seals. Under the combined effects of collision-related compression between the Luconia Block and Kalimantan and structural deformation along the Tinjar–Sabalan Fault Zone, diverse structural traps developed, including buried hills, flower structures, fault blocks, inversion structures, and diapirs. These structures form key hydrocarbon traps and control fluid migration and accumulation. In the southern basin, compressional deformation produced fault blocks, faulted anticlines, drape folds, and rollover anticlines, which represent the dominant trap types. In contrast, reefal carbonate buildups form the primary traps on the western slope and Nankang Platform. Since the Oligocene, persistent strike-slip motion along the Tinjar–Sabalan Fault Zone has generated numerous subsidiary faults that serve as major hydrocarbon migration pathways. Early right-lateral motion enhanced vertical connectivity and fluid transport, whereas the Late Miocene transition to left-lateral motion improved fault sealing and trapping efficiency. Strike-slip intensity decreases southward, producing abundant flower structures in the northern Nankang Platform and western slope. In these areas, Oligocene–Lower Miocene source rocks are vertically linked to Middle–Upper Miocene carbonate reservoirs, forming characteristic “source–below,

reservoir–above” accumulation systems. In contrast, faults in the southern East Baram Depression became largely inactive after the Early Miocene, favoring the development of self-contained Oligocene–Lower Miocene petroleum systems (Figure 8).

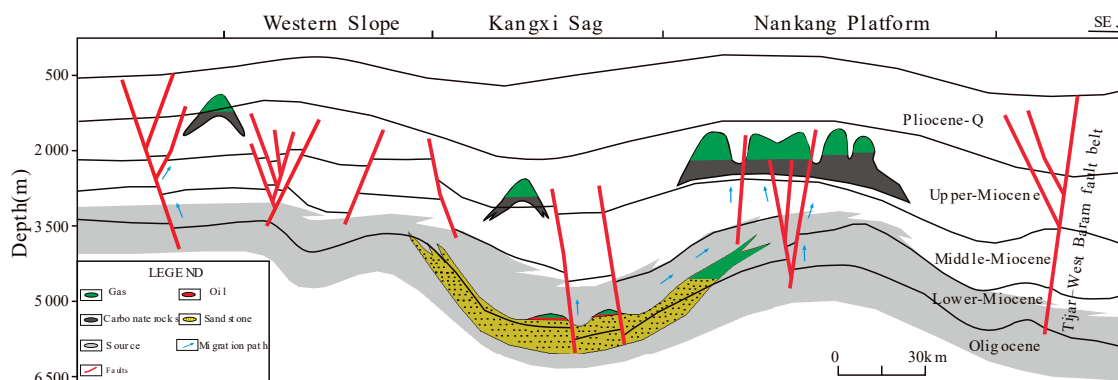


Figure 8. Hydrocarbon accumulation model of the Zengmu Basin (modified from [26]) (location shown in Figure 1).

5. Conclusions

This study area focuses on the Tinjar–West Baram Fault in the southern South China Sea, a major NW-trending strike-slip fault that defines the structural boundary between the Zengmu, Beikang, and Nansha Trough basins and has remained tectonically active since the Oligocene. Using 2D seismic profiles, this study analyzes the fault’s geometry and kinematics, and assesses its control on deep-water sedimentary systems in the Zengmu Basin; this study aims to improve constraints on the sedimentary response to the fault’s tectonic evolution. The main conclusions are summarized as follows:

1. **Spatiotemporal Differentiation of Sedimentary Systems under Tectonic Control:** Right-lateral strike-slip activity during the rifting stage exerted a primary control on basin architecture and the development of hydrocarbon “source” facies. During the Oligocene (32–25 Ma), seafloor spreading in the South China Sea induced dextral motion along the Tinjar–West Baram Fault Zone, generating extensional stress along the northwestern margin of the Zengmu Basin. This led to the formation of semi-graben depressions (e.g., the Kangxi Depression), where restricted circulation favored the deposition of organic-rich paralic carbonaceous shales and coal seams that constitute the basin’s primary source rocks. More than 8 km of Cenozoic strata record intense subsidence and sediment accumulation during this phase. Differential faulting produced an asymmetric basin geometry, characterized by a steep, fault-controlled northwestern margin and a gently dipping southern slope. Proximal fan-delta systems developed along the steep margin, whereas the shallow-marine deposits dominated the southeastern slope, establishing the fundamental spatial distribution of source and reservoir facies. During the Miocene (25–5 Ma), following cessation of seafloor spreading, the fault zone transitioned to left-lateral strike-slip with localized extension. This phase-controlled reservoir development and promoted southeastward depocenter migration toward the East Balingian Depression. Enhanced sediment supply related to the Sarawak Orogeny, resulted in the accumulation of thick marine mudstones (regional seals), reefal carbonate platforms (carbonate reservoirs), and deltaic to deep-water turbidite systems (clastic reservoirs). Secondary en échelon fault systems segmented the basin into a “basin–ridge” framework creating favorable structural and sedimentary conditions for hydrocarbon enrichment. Together with the thick Upper Miocene evaporites (200–500 m) and mudstone seals, a well-integrated “source–reservoir–seal” system developed, enabling vertically stacked, cross-stratal hydrocarbon accumulations involv-

ing Oligocene coal seams (gas-prone sources), Miocene sandstones and reefal limestones (reservoirs), and Pliocene mudstones (regional seals).

2. Petroleum Geological Implications of Tectono-Sedimentary Coupling: Strike-slip tectonism generated a dual-source, hydrocarbon system with contrasting thermal maturity. In the northern Kangxi Depression, shallow-water rift environments produced transitional facies source rocks dominated by Type II–III kerogen and primarily gas-prone potential. In contrast, deeper-water conditions in the southern East Balingian Depression favored the accumulation of Type I kerogen-rich marine mudstones, predominantly oil-prone [27,28]. This configuration defines a clear “southern oil–northern gas” distribution pattern. Localized mafic intrusions (e.g., diabase dikes) along the fault zone increased the geothermal gradient to ~45 °C/km, accelerating source-rock maturation and establishing the central basin as the main hydrocarbon generation center during 5–2 Ma. Strike-slip deformation produced three main trap types: (1) structural traps, including rollover anticlines, fault-blocks, and en échelon anticline clusters; (2) stratigraphic–lithologic traps, such as sandstone pinch-outs and reef–shoal carbonate buildups, and (3) compound traps combining inversion-related structures with unconformity-controlled stratigraphy. The main fault zone and its subsidiary faults form a broom-shaped fracture network that enhances vertical hydrocarbon migration (10–50 m/Ma) and locally increases reservoir permeability by 3–5 times. In compressional segments, fault gouge development and evaporite smearing improve sealing capacity, with breakthrough pressures exceeding 50 MPa.

3. Exploration Insights and Resource Potential: As a hydrocarbon-rich province in the southwestern South China Sea, the Zengmu Basin—strongly controlled by the Tinjar–West Baram Fault Zone—highlights Miocene reef–shoal complexes and strike-slip-related anticline clusters as priority exploration targets. The basin provides a representative geological model for hydrocarbon accumulation in strike-slip fault-controlled basins and offers important scientific and practical insights into tectono-sedimentary–accumulation coupling along the South China Sea plate margin.

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Article

Tectonic Control on Intrabasinal “Source-to-Sink” Systems and Sedimentary Responses: A Case Study of the Weixinan Low Uplift, Beibuwan Basin

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Abstract

Intrabasinal low uplifts in lacustrine rift basins are key targets for sedimentological and petroleum geological research, as they can act as local source areas and exert critical controls on intrabasinal “source-to-sink” systems. Due to the discontinuous sediment supply, these systems often demonstrate the subtle and intermittent nature, and their roles in the development of depositional systems are usually overlooked. To clarify the controlling effect of intrabasinal local provenances on sedimentary system evolution, this study reconstructed the dynamic tectonic evolution of the Weixinan Low Uplift in the Beibuwan Basin, and systematically analyzed its control on “source-to-sink” systems and sedimentary filling using integrated high-resolution 3D seismic, core, well logging and geochemical data. Our results demonstrate that the activity of Fault 3 dominated the paleogeomorphic evolution of the Weixinan Low Uplift and its surrounding areas, which further governed the spatiotemporal development of the “source-to-sink” system and the distribution of sedimentary systems, with distinct evolutionary stages as follows: During the Ls2 Member stage (48.6–40.4 Ma), Fault 3 was inactive, the Weixinan Low Uplift was manifested as a gently dipping subaqueous slope under the influence of regional lacustrine transgression, and only small-scale braided river deltas were developed on the slope belt with weak sediment supply from the Qixi Uplift. During the Ls1 Member stage (40.4–33.9 Ma), the Ls13 Sub-member stage (lower Ls1 Member stage) was characterized by initiation of Fault 3 with segmented activity, triggering the formation of the Eastern Sub-sag of the Haizhong Sag and subaqueous uplift of the Weixinan Low Uplift; clastic sediments from the central Qixi Uplift were transported northeastward, developed braided river deltas and large-scale basin-floor lacustrine fans. In the Ls12 Sub-member stage (middle Ls1 Member stage), Fault 3 continued to propagate and was gradually linked, leading to further uplift of the Weixinan Low Uplift and expansion of the Haizhong Sag; Clastic materials from the central Qixi Uplift were almost entirely trapped in the Eastern Sub-sag of the Haizhong Sag. During the Ls11 Sub-member stage (upper Ls1 Member stage), further intensification of Fault 3 activity caused the Weixinan Low Uplift to be subaerially exposed and evolve into an intrabasinal local provenance, which supplied clastic sediments to surrounding sags and developed braided river deltas on the gentle slope belts and small-scale lacustrine fans on the lower slope. This study demonstrates that the tectonic evolution of the Weixinan Low Uplift has induced prominent changes in the basin paleogeomorphology, which in turn triggered dynamic shifts in the provenance and sediment transport pathways, and thus gave rise to complex local “source-to-sink” systems and depositional styles.

Keywords: “source-to-sink” system; tectono-sedimentary response; basin geomorphology; Weixinan Low Uplift; Haizhong Sag; Beibuwan Basin; South China Sea

1. Introduction

The “source-to-sink” system describes the complete pathway of sediment from erosion in source areas, through transport pathways, to final deposition in sink areas [1–3]. With its inherent advantages of high quantification, high accuracy and strong predictability, “source-to-sink” analysis has become a key topic and frontier field in numerous major international geoscience research programs [4]. Its spatiotemporal scope continues to expand, encompassing modern systems (10^2 – 10^3 years), deep-time systems (2.5×10^6 – 10^8 years) [5], and settings ranging from oceanic-continental margins to intracontinental rift basins. While most classic “source-to-sink” studies have focused on large paleocontinents, paleouplifts, and orogenic belts at basin margins (i.e., extrabasinal sources), which provide long-term, stable clastic sediment supply, recent years have seen a paradigm shift as oil and gas exploration advances progressively into basin depocenters. It has been increasingly recognized that small, low-relief, paleohighlands (low uplift), or structural dip terminations within basins can also act as significant provenances, supplying clastic material to adjacent areas and developing commercial-scale oil and gas reservoirs. A series of pioneering studies have advanced the understanding of such intrabasinal “source-to-sink” systems: Xu et al. [6] summarized eight local source-controlled sedimentation patterns based on the spatiotemporal coupling principles governing faulted lacustrine basin “source-to-sink” systems. Du et al. [7] proposed three types of source concealment patterns (sequence, tectonic, material), indicating that parent rock type, fault activity, and tectonic style are the primary controlling factors for sand enrichment within local “source-to-sink” systems. Hu et al. [8] established a coupled sand control model linking effective source area to sediment transport pathways in local “source-to-sink” systems through quantitative calculations. Zhu et al. [9] indicated that local source areas, if meeting conditions such as large effective source area and significant topographic elevation difference, may develop large reservoirs within sediment sink areas. Despite these important foundational advances, systematic research on such intrabasinal local “source-to-sink” systems remains limited to date, largely due to their pronounced characteristics of concealment, intermittency, and dynamism.

The Beibuwan Basin constitutes a Cenozoic rift basin along the northern margin of the South China Sea, hosting multiple hydrocarbon-prone depressions, including the Weixinan Depression [10]. Following years of exploration and development, primary depressions within the Weixinan Depression (e.g., Sub-sag A and Sub-sag B) have reached high exploration maturity, necessitating urgent expansion into new exploration areas. In recent years, oil and gas discoveries have been made in marginal basins surrounding the Weixinan Low Uplift, indicating substantial exploration potential [11–13]. However, due to complex multi-phase faulting, the tectonic evolution of the Weixinan Low Uplift remains poorly understood. This uncertainty has led to debates regarding the spatiotemporal distribution of the “source-to-sink” system and sedimentary system in the Weixinan Low Uplift and its surrounding sub-sags, thereby constraining predictions of high-quality hydrocarbon source rocks and favorable reservoirs. Therefore, this study reconstructs the tectonic and geomorphic evolution of the Weixinan Low Uplift to characterize the spatiotemporal evolution of its local “source-to-sink” systems, and decipher how tectonic activity controlled sediment transport pathways and depositional patterns. This aims to provide a basis for predicting hydrocarbon source rocks and sandstone reservoirs,

while also offering insights for studying localized “source-to-sink” systems within other terrestrial basins.

2. Geological Setting

The Beibuwan Basin lies north of the Hainan Uplift and south of the Yuegui Uplift, with a total area of $3.98 \times 10^4 \text{ km}^2$ [14–16]. The basin exhibits “two sags sandwiching one uplift” and is divided from north to south into three secondary structural units, such as the Northern Depression Zone, Qixi Uplift, and the Southern Depression Zone [17,18] (Figure 1a). The Northern Depression Zone constitutes a key exploration target for oil and gas in the basin, and is further subdivided into the Weixinan Low Uplift, Weixinan Sag, and Haizhong Sag. Extending roughly in a NEE direction in the center of the Northern Depression Zone, the Weixinan Low Uplift separates the northern Weixinan Sag (containing Sub-sag A, Sub-sag B, and Sub-sag 11, etc.) from the southern Haizhong Sag (containing Eastern Sub-sag and Western Sub-sag) (Figure 1b). Driven by the activity of multi-level and multi-episodic faults, the Weixinan Low Uplift exhibits complex structures. Its evolutionary history, particularly the timing of initiation and evolution processes, as well as its spatial extent, has remained a controversial topic [19–22].

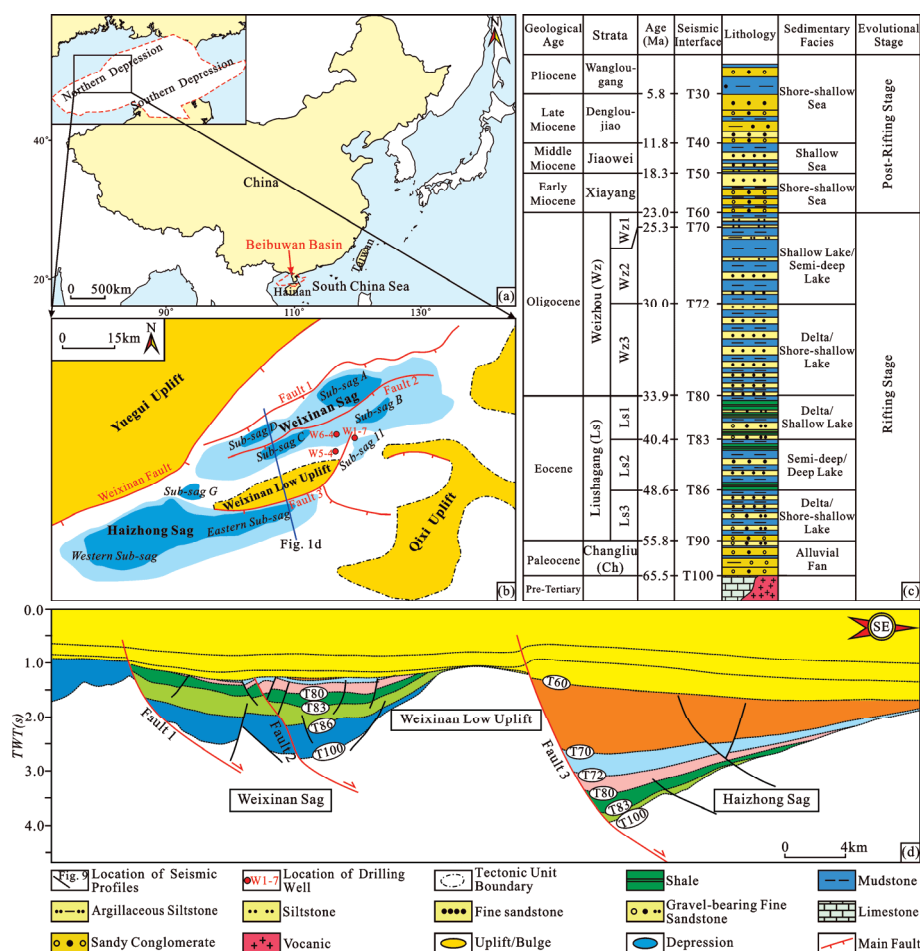


Figure 1. Structural units and tectonic-stratigraphic framework of the Northern Depression of the Beibuwan Basin [14–20]. (a) Location of the Beibuwan Basin in China. (b) Major structural units of the Weixinan Low Uplift and its surrounding areas. (c) Tectono-stratigraphic chart of the Beibuwan Basin. (d) Tectono-stratigraphic profile of the Weixinan Low Uplift, Weixinan Sag and Haizhong Sag.

The sedimentary strata in the Northern Depression are sequentially divided from oldest to youngest into the Paleocene Changliu Formation (Ch, 65.5–55.8 Ma), Eocene Liusha-

gang Formation (Ls, 55.8–33.9 Ma), Oligocene Weizhou Formation (Wz, 33.9–23.0 Ma), Lower Miocene Xiayang Formation (23.0–18.3 Ma), Middle Miocene Jiaowei Formation (18.3–11.8 Ma), Upper Miocene Denglouliao Formation (11.8–5.8 Ma), and Pliocene Wanglougang Formation (5.8–0 Ma) (Figure 1c). Dominated by alluvial fan and fluvial facies, the Changliu Formation was deposited during the initial rifting stage of the Beibuwan basin. The Liushagang Formation is further subdivided into three members: Ls3 Member, Ls2 Member, and Ls1 Member. Specifically, Ls3 Member is characterized by fan delta and shore-shallow lake facies; Ls2 Member is dominated by thick-bedded mudstone-shale deposits of middle-deep lake facies; and Ls1 Member contains fan delta, braided river delta, sublacustrine fan, and shore-shallow lake facies. Based on differences in tectonic activity and lake-level fluctuations, Ls1 Member can be further refined into three evolutionary stages (early, middle, and late), corresponding to the Ls13, Ls12, and Ls11 Sub-members, respectively. The Weizhou Formation is dominated by marine-continental transitional facies such as fan delta, braided river delta, and beach bar, reflecting the basin transition from the rifting stage to the post-rifting stage. Furthermore, the Xiayang, Jiaowei, Denglouliao, and Wanglougang Formations are mainly composed of shore-shallow marine facies [23–25].

3. Dataset and Methods

3.1. Dataset

All datasets used in this study were provided by CNOOC Zhanjiang Branch (Zhanjiang, China), including high-precision 3D seismic, core, drilling-logging, and geochemical datasets covering the Weixinan Low Uplift and its surrounding areas in the Northern Depression. The 3D seismic data were processed via Pre-Stack Time Migration (PSTM) with a frequency range of 30–45 Hz, TWT of ~6 s, and a line spacing of 12.5 m. Covering an area of ~5000 km² (encompassing the Weixinan Sag and the Eastern Sub-sag of the Haizhong Sag), this seismic dataset enables clear visualization of stratigraphic interfaces, faults, and sedimentary body geometries. Core samples were obtained from 10 wells in the study area, with a total length of ~200 m, which provide direct evidence for the identification of lithologies and sedimentary structures (Table 1). Well logging data include lithological records, well logs, and sediment grain size analysis results from over 300 drill wells, which aid in stratigraphic division and sedimentary facies identification. Geochemical datasets consist of heavy mineral analysis data, primarily used for the discrimination of potential source areas.

Table 1. Basic information of cored wells used in this study.

Well Name	Core Intervals	Strata
W1-1	2682.37–2688.62 m	Ls3
	2715.45–2730.80 m	Ls3
	2897.00–2915.00 m	Ls3
	2932.00–2939.70 m	Ls3
	2569.00–2572.70 m	Ls3
	2603.35–2606.76 m	Ls3
W1-4	2504.10–2517.52 m	Ls1
W1-7	1836.20–1845.30 m	Ls2
W1-10X	2658.00–2701.87 m	Ls3
W2-1	1868.00–1869.27 m	Ls1
W2-4	1876.00–1877.75 m	Ls1
W2-7	2082.61–2091.96 m	Ls2
	2574.30–2583.36 m	Ls3
W2-8	2985.38–2989.29 m	Ls3
	3001.34–3008.23 m	Ls3
W5-4	1505.00–1512.56 m	Ls1
W6-4	2190.50–2228.78 m	Ls1

3.2. Methods

3.2.1. Tectono-Stratigraphic Framework

Stratigraphic interfaces were dated and characterized using well logging data. High-precision interpretation of 3D seismic data was conducted with DSG software (Version 10ep 5.2). Eight key stratigraphic interfaces in the study area were identified: T100 (65.5 Ma), T90 (55.8 Ma), T86 (48.6 Ma), T83 (40.4 Ma), T80 (33.9 Ma), T72 (30.0 Ma), T70 (25.3 Ma), and T60 (23.0 Ma). Based on these interfaces, a high-precision tectono-stratigraphic framework of the study area was established. Additionally, taking Well W2-3 in the northeastern Weixinan Sag as the constraint well (drilled to a depth of ~3200 m in the Changliu Formation), comprehensive analysis was conducted on 3D seismic profiles and well logging data from over 100 wells. This enabled accurate time-depth conversion, which was essential for subsequent tectonic evolution analysis and quantitative calculations.

3.2.2. Stratigraphic Erosion Amount and Fault Activity Analysis

Building on the high-precision tectono-stratigraphic framework and accurate time-depth conversion results, the stratigraphic trend method was employed to calculate the stratigraphic erosion amount during the Liushagang Formation [26], and the “paleo-throw-distance method” was adopted for fault activity analysis. Specifically, more than 30 sampling points were selected from multiple seismic profiles orthogonal to the strike of Fault 3 and crossing the Weixinan Low Uplift. Seismic time data were converted to depth data via time-depth conversion technology, and the difference in stratigraphic thickness between the hanging wall and footwall of the fault (i.e., paleo-throw) at each sampling point during different sedimentary periods was measured to reflect the activity intensity of Fault 3 [27,28]. The activity characteristics of Fault 3 were systematically analyzed by statistically evaluating the maximum and average paleo-throw of the eastern segment, western segment, and turning point of Fault 3 during each sedimentary period.

3.2.3. Tectonic Paleogeomorphology Reconstruction

Combined with the results of fault activity analysis, residual stratigraphic thicknesses between successive stratigraphic interfaces were extracted from seismic data and drilling-logging stratigraphic data, and residual thickness contour maps covering the study area were constructed. Finally, by superimposing the erosion amount and residual stratigraphic thickness, and integrating basin subsidence history analysis, the tectonic paleogeomorphology of the study area during the Liushagang Formation was reconstructed [29,30].

3.2.4. Provenance Analysis

On the basis of tectonic paleogeomorphology reconstruction, relied on heavy mineral analysis data from numerous drilling samples in the study area, seven most representative heavy minerals (Zircon, Tourmaline, Rutile, Garnet, Hematite-Limonite, Magnetite, and Leucoxene) were selected. The heavy mineral relative content characteristic method and ZTR (Zircon-Tourmaline-Rutile) index method were applied to conduct comprehensive analysis on the sediment input characteristics of potential source areas. Specifically, the relative content characteristic method identifies potential source areas and delineates their influence ranges by tracking the spatial distribution of relative contents of typical heavy minerals [31]. The ZTR index method evaluates the direction of sediment transport based on the ratio of the sum of relative contents of Zircon, Tourmaline, and Rutile to the total amount of transparent heavy minerals [32,33].

3.2.5. Paleodrainage System Reconstruction

Based on the aforementioned source areas discrimination results and tectonic paleogeomorphology characteristics, this study drew on the method proposed by Lu et al. [34] for dividing paleodrainages using lines of structural highs (derived from modern geographical drainage division). Combined with the spatiotemporal distribution patterns of sediment transport pathways in the Weixinan Low Uplift, lines of paleogeomorphological highs were used as the core criterion for dividing boundaries between source areas at all levels, enabling systematic characterization of the paleodrainage systems in the Weixinan Low Uplift and its surrounding areas.

4. Results

4.1. Tectonic Evolution Characteristics

4.1.1. Fault Activity Analysis

Large-scale faults developed in rift basins not only control the tectonic framework of the basin but also affect the “source-to-sink” system and sedimentary filling by developing differential tectonic landforms (e.g., intrabasinal low uplift) [2]. In the Weixinan Low Uplift and its surrounding areas, the fault system was well developed. The NE- and NEE-trending (or nearly EW-trending) faults are relatively large in scale, mostly being basin-controlling or sag-controlling faults, which played a dominant role in the evolution of the Weixinan Low Uplift and changes in tectonic paleogeomorphology. In contrast, the NW-trending faults were mainly Sub-sag-controlling faults, which primarily affect subordinate structural units [35–38]. There were four major extensional normal faults developed in the study area, namely the Weixinan Fault, Fault 1, Fault 2 and Fault 3. The Weixinan Fault and Fault 1 jointly form the northern boundary of the Northern Depression and were basin-controlling faults that influence the formation and development of the basin (Figure 1b). Fault 2 was located in the northeastern part of the Weixinan Sag and was an en echelon strike-slip fault developed within the sag (Figure 1b) [18,39,40]. Fault 3 was situated in the southern part of the Weixinan Low Uplift and generally presented an arc-shaped convex to the southeast, exerting an important controlling effect on the tectonic evolution of the Weixinan Low Uplift and the Haizhong Sag (Figure 1b).

Based on differences in strike, Fault 3 can be further divided into eastern and western segments. The western segment, with an NEE strike, constitutes the main body of Fault 3, while the eastern segment turns to an NE strike. This study conducted a detailed quantitative analysis of the activity of Fault 3 (Figure 2a) and reconstructed the evolutionary process during the different sedimentary periods of the Liushagang Formation.

Before the stage of the Ls1 Member, the paleo-throw values at all sampling points on Fault 3 were 0, indicating that Fault 3 was not yet active (Figure 2c). During the Ls13 Sub-member stage, the maximum paleo-throw value at each sampling point on the western segment of Fault 3 was 0.53 km, with an average of 0.33 km; the maximum paleo-throw at each sampling point on the eastern segment was 0.23 km, with an average of 0.11 km, and the paleo-throw value at the turning point was 0. This indicates initial, segmented development of Fault 3, with greater activity in the western segment (Figure 2d). During the Ls12 Sub-member stage, the maximum paleo-throw value of the western segment of Fault 3 reached 0.89 km, with the average increased to 0.62 km; the maximum paleo-throw value of the eastern segment was 0.41 km, with the average increased to 0.23 km, and the average paleo-throw value at the turning point was 0.14 km. These values demonstrate intensified activity of Fault 3 during this period, and the eastern and western segments were gradually linked (Figure 2e). During the Ls11 Sub-member stage, the maximum paleo-throw value of the western segment of Fault 3 was 1.44 km, with the average increased to 1.11 km; the maximum paleo-throw value of the eastern segment was 0.72 km, with the average

increased to 0.48 km, and the average paleo-throw value at the turning point increased to 0.33 km. This indicates that the activity of Fault 3 further intensified during this period, and the eastern and western segments were completely linked (Figure 2f), which exerted a significant impact on the development and distribution of tectonic paleogeomorphologies such as uplifts and sags [41].

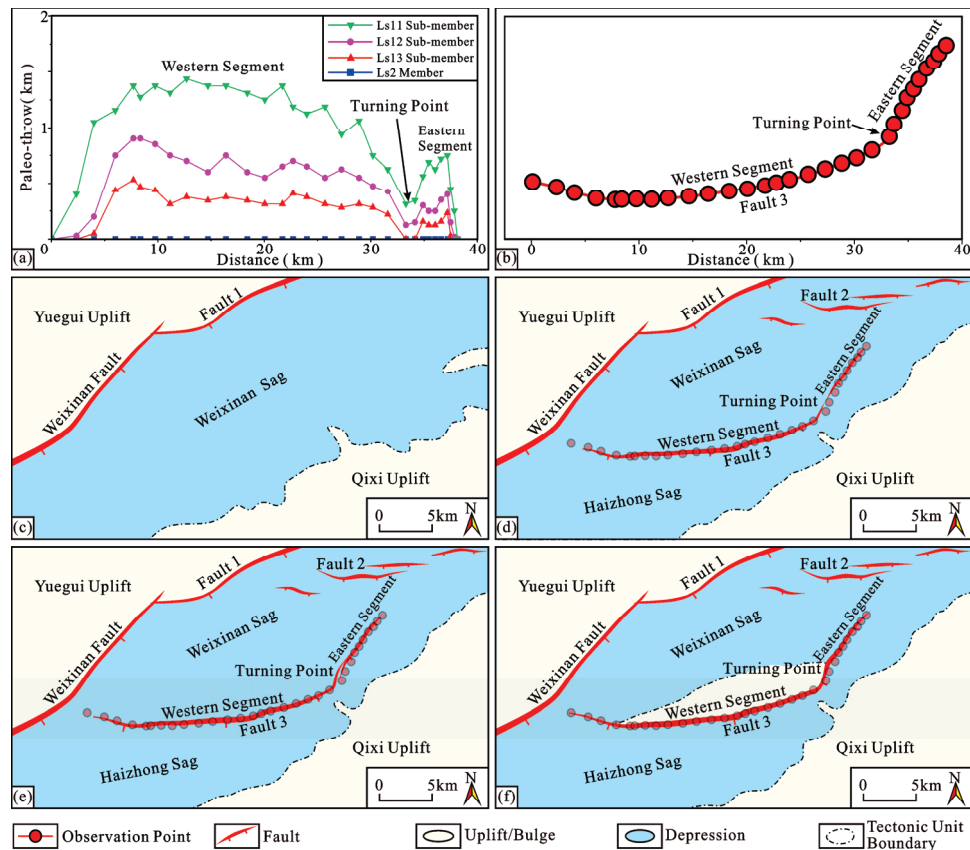


Figure 2. Analysis of activity characteristics of the Weixinan Low Uplift and its surrounding faults. (a) Paleo-throw-distance diagram of Fault 3. (b) Locations of sampling points of Fault 3. (c) Major faults in the Ls2 Member stage. (d) Major faults in the Ls13 Sub-member stage. (e) Major faults in the Ls12 Sub-member stage. (f) Major faults in the Ls11 Sub-member stage.

4.1.2. Reconstruction of Tectonic Paleogeomorphology

The original geomorphology of a basin was a key controlling factor affecting sedimentary filling [42]. After years of research, scholars have proposed a variety of methods for reconstructing the tectonic paleogeomorphology of basins (e.g., stratigraphic backstripping method, strata denudation quantity restoration method, fault paleo-throw quantitative calculation method, and impression method, etc.). However, different methods have different applicable conditions, and each method has certain limitations [43–46]. In view of the available dataset and geological characteristics of the study area (characterized by severe strata denudation around the Weixinan Low Uplift), supported by high-precision 3D seismic data and well logging data, the tectonic paleogeomorphology of the study area was reconstructed using the original strata thickness restoration method, which is calculated as the sum of denuded strata thickness and residual strata thickness.

The interval from the Changliu Formation to the Ls3 Member stage was characterized by activity along NE-trending faults (e.g., the Weixinan Fault and Fault 1). Sedimentary strata were restricted to Sub-sag A of the Weixinan Sag and the Western Sub-sag of the Haizhong Sag. During this period, the Weixinan Low Uplift had not yet developed, and

this area where it is located showed a nearshore slope, with strata gradually thickening northward (Figure S1).

During the Ls2 Member stage, the intense activity of Fault 1 controlled the development of the Weixinan Sag. The scope of the basin expanded significantly, and accompanied by regional lacustrine transgression, a pattern of extensive distribution of semi-deep/deep lake facies was developed. During this period, the nearshore slope at the location of the Weixinan Low Uplift gradually evolved into a gently inclined subaqueous slope (Figure 3a).

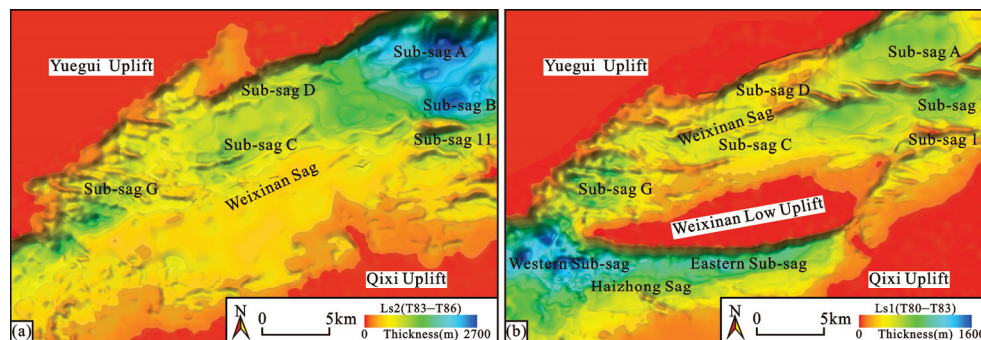


Figure 3. The tectonic paleogeomorphology of the Weixinan Low Uplift and its surrounding areas. (a) Ls2 Member. (b) Ls1 Member.

In the Ls13 Sub-member stage, Fault 3 initiated, with activity concentrated in its western segment, triggering differential subsidence across the fault. The hanging wall of the Fault 3 subsided rapidly, leading to the gradual development of the Eastern Sub-sag of the Haizhong Sag; and the footwall of the Fault 3 gradually tilted upward. Furthermore, the activity of the eastern segment of the fault was relatively weak, and a transfer slope was developed in the transition zone between the eastern and western segments.

During the Ls12 Sub-member stage, Fault 3 was characterized by sustained activity with increased intensity, and its eastern and western segments were gradually linked. Controlled by this fault activity, the Eastern Sub-sag of the Haizhong Sag, located on the hanging wall of Fault 3, expanded progressively in scale, while the footwall of Fault 3 was further uplifted to develop a subaqueous low uplift.

In the Ls11 Sub-member stage, Fault 3 underwent a further intensification of activity. This intense tectonic activity drove rapid tilting, uplift, and eventual subaerial exposure of the fault's footwall, developing the Weixinan Low Uplift—a half-horst bounded and controlled by the Fault 3. Meanwhile, the hanging wall of Fault 3 experienced strong subsidence, which triggered the rapid expansion of the Eastern Sub-sag of the Haizhong Sag. By this stage, the Weixinan Sag and Haizhong Sag were essentially separated by this newly emergent half-horst low uplift, establishing the definitive geomorphic framework of “two sags sandwiching one uplift” in the Northern Depression (Figure 3b).

4.2. Reconstruction of the “Source-to-Sink” Systems

The local “source-to-sink” system is an important form of material transport and sediment accumulation within a basin. The differential paleogeomorphology controlled by fault activity exerts a significant influence on its development [247]. Based on the restoration of the tectonic evolution process of the Weixinan Low Uplift and its surrounding areas, this study conducted analyses including the identification of potential source areas, the detailed characterization of sediment transport pathways, and the spatiotemporal evolution characteristics of sedimentary systems. The aim is to reconstruct the “source-to-sink” system of the Weixinan Low Uplift and its surrounding areas.

4.2.1. Identification of Potential Source Areas

Comprehensive comparative analysis of detrital zircon U-Pb geochronology and basement lithology indicates that the main source areas of the Northern Depression in the Beibuwan Basin are the Yuegui Uplift (including the Shiwandashan Mountains, Yunkai Block, etc.) in the north and the Qixi Uplift in the south [16,20,48–50]. However, in-depth analysis is still needed regarding the redistribution mechanism of clastic materials input from these extrabasinal source areas within the basin, as well as the contribution of small-scale local sources (such as intrabasinal low uplifts) to the “source-to-sink” system.

To address the aforementioned research gap, this study analyzed the heavy mineral data of samples from the Ls1 Member in multiple wells within the study area. Significant differences exist in heavy mineral compositions between northern and southern well samples. Among these samples, those from the northern part (Wells 1 to 5) are characterized by high garnet content and low leucoxene content, whereas those from the southern part (Wells 6 to 23) exhibit the opposite characteristics. Combined with previous analyses of basement lithology and detrital zircon dating results in the study area [16,48], two extrabasinal potential source areas were identified: the northern Yuegui Uplift and the southern Qixi Uplift.

Using the identified potential source areas, along with the relative content of various heavy minerals and the distribution trend of the ZTR index, this research further delineated the influence range and approximate transport direction of clastic materials input from extrabasinal source areas into the basin. During the deposition of the Ls1 Member, the relative content of hematite-limonite in samples from Wells 1 and 2 was higher than 18%, while that in samples from Wells 3 to 5 was lower than 15%. Combined with the location of the wells, it is inferred that the sediments in the area of Wells 1 and 2 were supplied by the central source area of the Yuegui Uplift, with clastic materials transported approximately from northwest to southeast; the sediments in the area of Wells 3 to 5 were supplied by the eastern source area of the Yuegui Uplift, with clastic materials transported approximately from north to south. In contrast, the input and distribution of clastic materials supplied by the Qixi Uplift source area within the basin were more complex. During the stage of the Ls13 Sub-member, the relative content of zircon in samples from Wells 6 and 18 to 23 was higher than 17%, while that in samples from Wells 7 to 17 was lower than 14%. It is thus inferred that the sediments in the area of Wells 6 and 18 to 23 were mainly supplied by the central source area of the Qixi Uplift, with clastic materials transported approximately from south to north; the sediments in the area of Wells 7 to 17 were mainly supplied by the eastern source area of the Qixi Uplift, with clastic materials transported approximately from southeast to northwest (Figure 4a,d). In the Ls12 Sub-member stage, the relative content of zircon in samples from Well 6 was approximately 29%, while that in samples from Wells 7 to 23 was lower than 20%. Therefore, it is considered that the sediments in the area of Well 6 were mainly supplied by the central source area of the Qixi Uplift, with clastic materials transported approximately from south to north; the sediments in the area of Wells 7 to 23 were mainly supplied by the eastern source area of the Qixi Uplift, with clastic materials transported approximately from southeast to northwest (Figure 4b). In the Ls11 Sub-member stage, the relative content of hematite-limonite in samples from Wells 18 to 23 was higher than 25%, which was in sharp contrast to other surrounding wells where hematite-limonite was almost absent. As mentioned earlier, during the deposition of the Ls11 Sub-member, the Weixinan Low Uplift had been exposed above the water surface, and Wells 18 to 23 were just adjacent to the tilted termination on the eastern side of the Weixinan Low Uplift. This suggests that sediments in this area were primarily sourced from the newly exposed Weixinan Low Uplift at this time, with clastic materials transported approximately from southwest to northeast (Figure 4c,e).

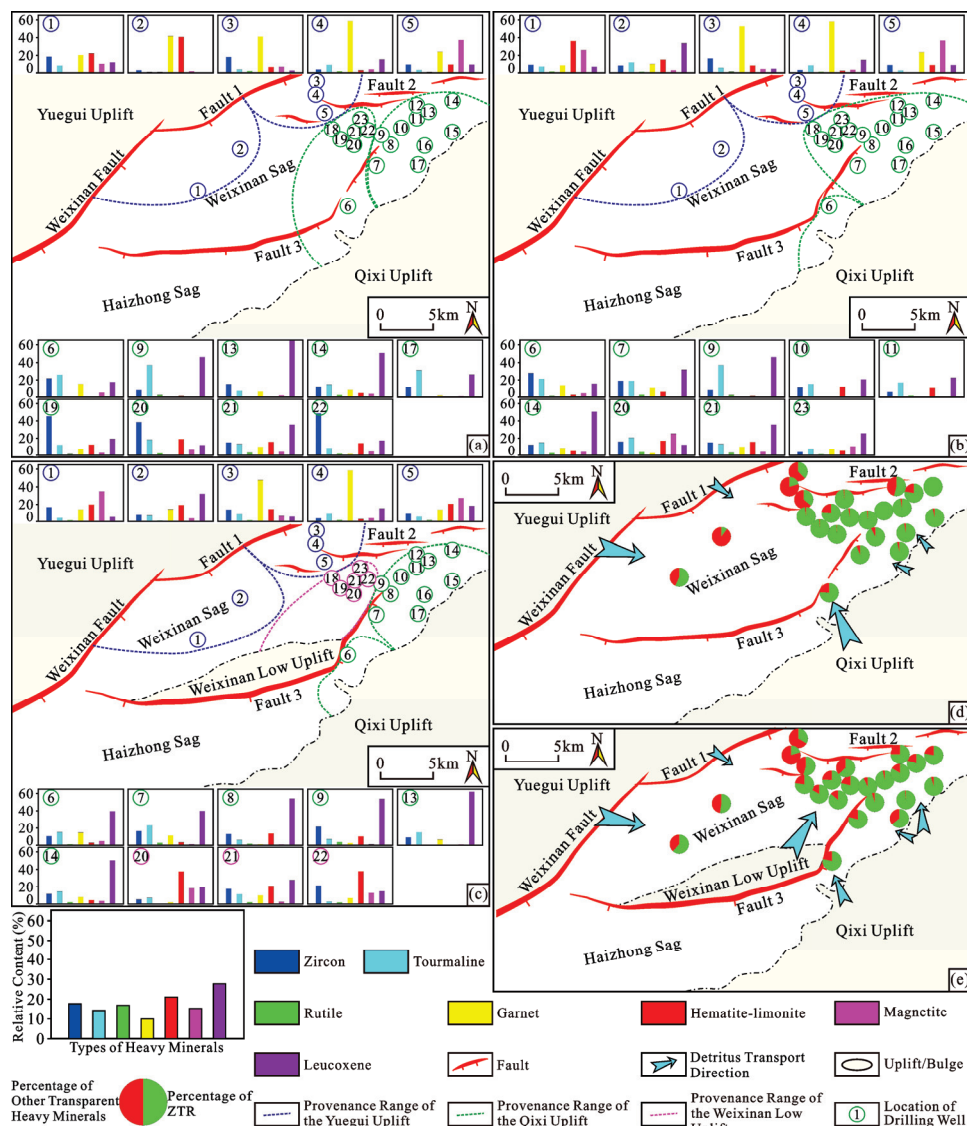


Figure 4. Characteristics of relative heavy mineral content and ZTR index of the Ls1 Member in the periphery of the Weixinan Low Uplift. (a) Relative heavy mineral content distribution of the Ls13 Sub-member. (b) Relative heavy mineral content distribution of the Ls12 Sub-member. (c) Relative heavy mineral content distribution of the Ls11 Sub-member. (d) ZTR index distribution of the Ls13 Sub-member. (e) ZTR index distribution of the Ls11 Sub-member.

4.2.2. Sediment Transport Pathways

Sediment transport pathways serve as the critical link between source areas and sedimentary sinks. Their accurate identification clarifies transport paths and helps elucidate the mechanism by which tectonic activities influence the types of transport pathways through modifying paleogeomorphology, thereby providing a scientific basis for predicting the distribution of sandbodies.

Detailed seismic facies interpretation reveals three main types of sediment transport pathways—incised valleys, fault troughs, and slope belts—can be identified in the Weixinan Low Uplift and its surrounding areas. Incised valleys are mainly distributed on the northern and western sides of the Weixinan Low Uplift and were developed throughout the Liushagang Formation. Their morphological characteristics exhibit significant differences across different structural locations. On the upper-middle part of the slope, due to the large overall uplift amplitude of the strata and the steep slope gradient, the original strata were strongly modified by fluvial erosion. On seismic profiles, the incised valleys typically

show V-shaped features with clear boundaries and prominent down-cutting and lateral erosion (Figure 5a). On the lower-middle part of the slope, the uplift amplitude of the strata decreases, the slope gradient becomes gentle, and the fluvial erosion capacity weakens significantly. On seismic profiles, the incised valleys then exhibit broad and gentle U-shaped or W-shaped features (Figure 5b).

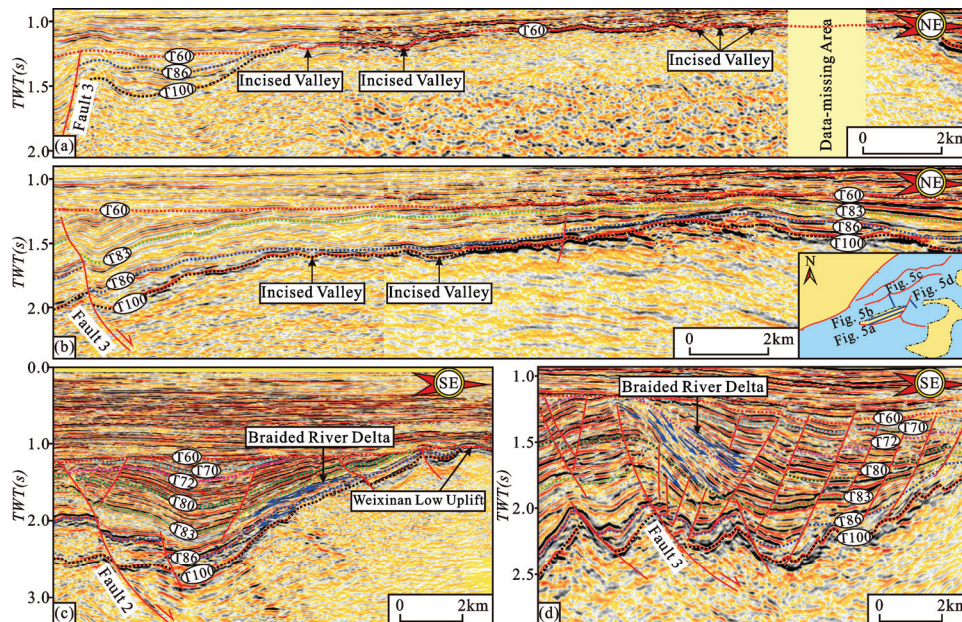


Figure 5. Typical seismic reflection characters of sediment transport pathways in the Weixinan Low Uplift and its surrounding areas. (a) Incised valley on the upper-middle part of the northern margin of the Weixinan Low Uplift. (b) Incised valley on the lower-middle part of the northern margin of the Weixinan Low Uplift. (c) Gentle slope zone on the northern part of the Weixinan Low Uplift. (d) Flexural slope break zone on the northeastern part of the Weixinan Low Uplift. Blue arrows (c,d) indicate the foreset reflections of braided river deltas.

Fault troughs are mainly distributed on the northwestern side of the Weixinan Low Uplift. A series of secondary faults obliquely intersecting the strike of the Weixinan Fault develop in this area and jointly form the fault troughs. During the Liushagang Formation, clastic materials from the source area of the Yuegui Uplift were mainly transported southeastward along this transport channel and accumulated in the basin.

Slope belts of various types are widely developed in all directions around the Weixinan Low Uplift. Fault-controlled steep slope belts are mainly distributed along the southern margin of the Weixinan Low Uplift, their formation is primarily controlled by the intense activity of Fault 3. Due to the close distance to the source area and significant topographic relief, fan deltas are mainly developed on them. Gentle slope belts mainly distributed on the northern part of the Weixinan Low Uplift, they are gently inclined slopes developed under the background of relatively weak tectonic activity, and are dominated by the development of braided river delta (Figure 5c). Flexural slope break belts mainly distributed on the northeastern part of the Weixinan Low Uplift. They are developed by the flexure of the overlying strata caused by the gradual weakening of the activity of the eastern segment of Fault 3, which eventually evolved into concealed activity. These belts control the transport and accumulation of clastic materials from the source area on the eastern side of the Weixinan Low Uplift (Figure 5d).

4.2.3. Distribution of Paleodrainage Systems in the Weixinan Low Uplift and Its Surroundings

Applying the paleodrainage division concept of Lu et al. [34], this research identified the grade I watershed in the Weixinan Low Uplift by tracing the line connecting the highest points along the east–west axis, and this watershed further divided the surrounding drainage systems into two major drainage areas (northern and southern) with roughly opposite water flow directions.

The northern drainage area of the Weixinan Low Uplift corresponds to the gentle slope belt, featuring an open terrain and a wide convergence range of drainage systems, thus developing the northern grade I source area. The southern drainage area of the Weixinan Low Uplift corresponds to the steep slope belt, where the distribution range of drainage systems is limited due to the strong constraint of boundary faults, thus developing the southern grade I source area. Within the two major grade I source areas, grade II divides were delineated based on the connecting lines of secondary tectonic high points to separate the secondary basins controlled by individual water flows. The secondary tectonic high points on the northern gentle slope belt of the Weixinan Low Uplift are easy to identify, and the distribution characteristics of sediment transport pathways such as incised valleys are clear, allowing the division of three grade II source areas. Combined with the spatial distribution characteristics of microtopography, Sink areas 1–4 were further divided on the lower part of the northern gentle slope belt of the Weixinan Low Uplift. In contrast, the development characteristics of secondary tectonic high points on the southern steep slope belt of the Weixinan Low Uplift are not obvious, making it difficult to clearly define the grade II divide. Therefore, the lower part of the southern steep slope belt was collectively divided into Sink area 5 (Figure 6).

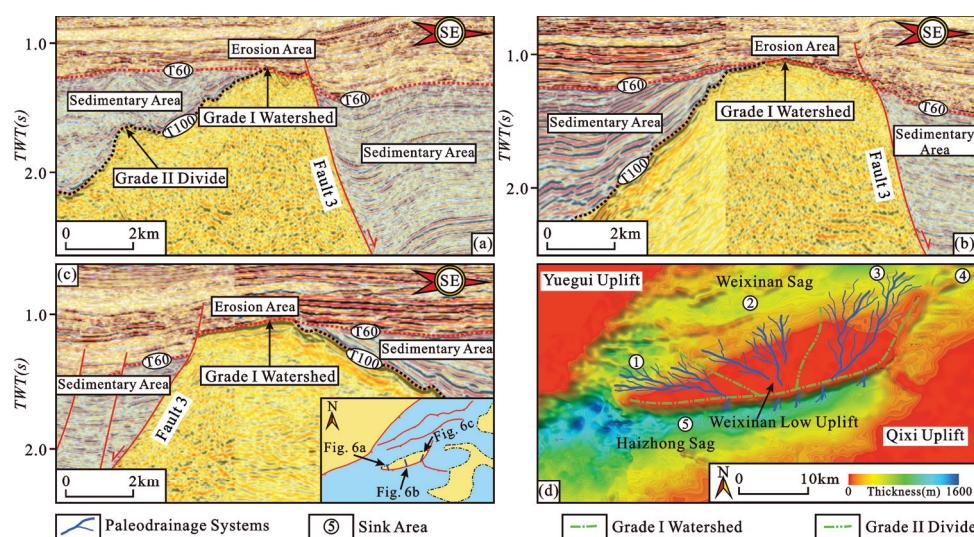


Figure 6. Division of watersheds and paleodrainage systems on the Weixinan Low Uplift. (a) Western watershed on the Weixinan Low Uplift. (b) Middle watershed on the Weixinan Low Uplift. (c) Eastern watershed on the Weixinan Low Uplift. (d) Paleodrainage system distribution of the Ls11 Sub-member.

4.2.4. Spatiotemporal Distribution Characteristics of Sandbodies on the Periphery of the Weixinan Low Uplift

To verify the spatiotemporal matching relationship between sediment supply from source areas and sandbody accumulation in sink areas within the “source-to-sink” system, this research finely characterized the spatiotemporal distribution characteristics of sandbodies during each sedimentary period of the Ls2 Member and Ls1 Member in the

Weixinan Low Uplift and its surrounding areas, based on sandbody thickness statistics from multiple drill wells.

During the Ls2 Member stage, a large-scale lacustrine transgression occurred in the study area, with sandbodies distributed in a scattered and thin-bedded pattern (Figure 7a). The sandbody thickness centers on the northern part are mainly distributed on the hanging wall of the eastern segment of the Weixinan Fault and the root of the hanging wall of the western segment of Fault 1; these sandbodies were supplied and accumulated by sources from the eastern and central parts of the Yuegui Uplift, transported southward and southeastward. The sandbody thickness centers on the southern part are mainly distributed on the eastern slope belt of the Qixi Uplift; they were supplied and accumulated by sediments from the Qixi Uplift, transported toward the north. In addition, extremely thin-bedded sandbodies are sporadically distributed in the center of the Weixinan Sag. It is inferred that these sandbodies were developed by the small-scale northward transportation and accumulation of sediments from the central source area of the Qixi Uplift along the subaqueous slope.

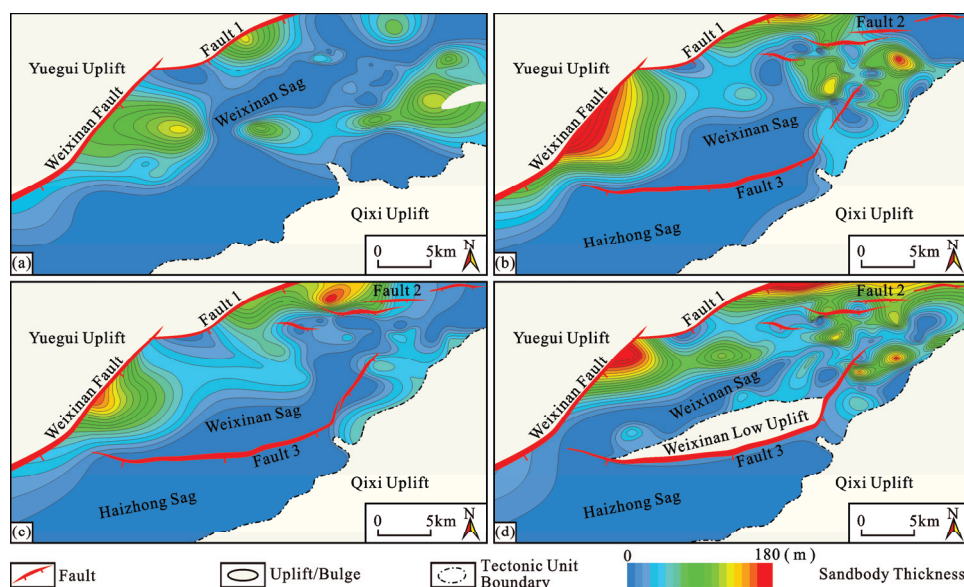


Figure 7. Spatial distribution of sandbodies on the Weixinan Low Uplift and its surrounding areas. (a) Ls2 Member. (b) Ls13 Sub-member. (c) Ls12 Sub-member. (d) Ls11 Sub-member.

During the Ls13 Sub-member stage, sandbodies in the study area were distributed in thick and continuous layers (Figure 7b). The northern sandbody thickness centers persisted and were distributed on the hanging wall east of the Weixinan Fault and at the root of the hanging wall on the western segment of Fault 1, with a significantly expanded distribution range (extending farthest to the center of the Weixinan Sag), indicating enhanced sediment supply from the Yuegui Uplift at this time. The southern sandbody thickness centers were inherited and distributed on the eastern slope of the Qixi Uplift, with sediments from the Qixi Uplift continuously supplied northward and the supply intensity increased. The most prominent feature of this period was the accumulation of thick-bedded sandbodies (with a maximum thickness of 120 m) in the sag center near the termination of the eastern segment of Fault 3. It is inferred that sediments from the central part of the Qixi Uplift were transported and accumulated northeastward along the transfer zone between the eastern and western segments of Fault 3 at this stage.

In the Ls12 Sub-member stage, the thickness of sandbodies in the study area decreased significantly (Figure 7c). Although the sandbodies supplied by the central source area of the Yuegui Uplift continued to advance eastward, their lateral distribution range narrowed

remarkably, indicating weakened sediment supply and reduced sediment input from the Yuegui Uplift at this time. The sandbodies supplied by the Qixi Uplift source area still advanced northward, but their overall thickness thinned significantly, developing only in a small range on the hanging wall of the eastern segment of Fault 3 and its surroundings. This reflects a notable decline in the sediment supply capacity of the Qixi Uplift compared with the previous stage.

During the Ls11 Sub-member stage, sandbodies in the study area were again distributed in thick and continuous layers (Figure 7d). The sandbodies supplied by the Yuegui Uplift source area further expanded on the hanging wall east of the Weixinan Fault and continued to advance eastward, reflecting the renewed enhancement of sediment supply from the Yuegui Uplift. The sandbodies supplied by the eastern source area of the Qixi Uplift continuously prograded northward along the eastern slope, and the sandbodies in the Weixinan Sag center thickened significantly. Small-medium-sized sandbodies gradually developed on the northern and eastern gentle slope belts of the Weixinan Low Uplift. The sandbodies developed on the eastern part are mainly distributed along the northeast direction, extending as far as the Sub-sag on the northeastern side of the Weixinan Low Uplift, and converging with sandbodies from other directions within the sag.

4.3. Sedimentary Responses of the Ls1 Member

Based on the aforementioned reconstruction of the “source-to-sink” system in the study area and its surroundings, combined with a comprehensive analysis of core facies, logging facies, and seismic facies, this research further identified the main types of sedimentary systems in the Ls1 Member of the study area, clarified the spatiotemporal distribution characteristics of the sedimentary systems, and analyzed the evolutionary patterns of the sedimentary systems.

4.3.1. Single-Well Sedimentary Characteristics

1. Sedimentary Characteristics of Well W1-7

Well W1-7 is located on the hanging wall at the terminal of the eastern segment of Fault 3 (Figure 1b). Seismic profiles show that a set of sedimentary bodies with a mounded shape and obvious bidirectional downlap reflections are developed in the Ls13 Sub-member in this well area, with internal characteristics of medium-high frequency, medium amplitude, and moderate continuity (Figure 8). Logging data indicate that in the Ls13 Sub-member: The lithology of the lower part is dominated by gravel-bearing grit sandstone and grit sandstone; The middle part transitions to fine sandstone and gravel-bearing medium sandstone; The upper part is mainly composed of fine sandstone. Overall, it presents a positive particle size cycle that becomes finer upward. The GR curve is mainly characterized by the superposition of multiple serrated box shapes and bell shapes.

The cored interval of 2504.10–2517.52 m in Well W1-7 show that multiple sets of vertically superimposed Bouma sequence Tc~Te intervals are developed in the Ls13 Sub-member. The Tc interval is dominated by gray fine sandstone, mostly with massive structure, and contains a small amount of plant detritus. The Td interval is mainly composed of gray argillaceous siltstone and silty mudstone, with developed wrinkle structures, deformed mud clasts, etc., and ripple laminations and flame structures are visible. The Te interval is dominated by gray-black mudstone, with extensive development of horizontal laminations and ripple laminations, and injectites and isolated sandy lenses can be observed inside (Figures 8 and S2). The cumulative probability curves of sediment grain size mainly show two types: the three-segment type and the broad gentle upward-arching type. The particle size is concentrated in the range of 4Φ and above, and the slope of each component is small. Comprehensive analysis of the above characteristics indicates that the Ls13 Sub-member in

this cored interval of Well W1-7 is dominated by sand-rich sublacustrine fan reworked by traction currents.

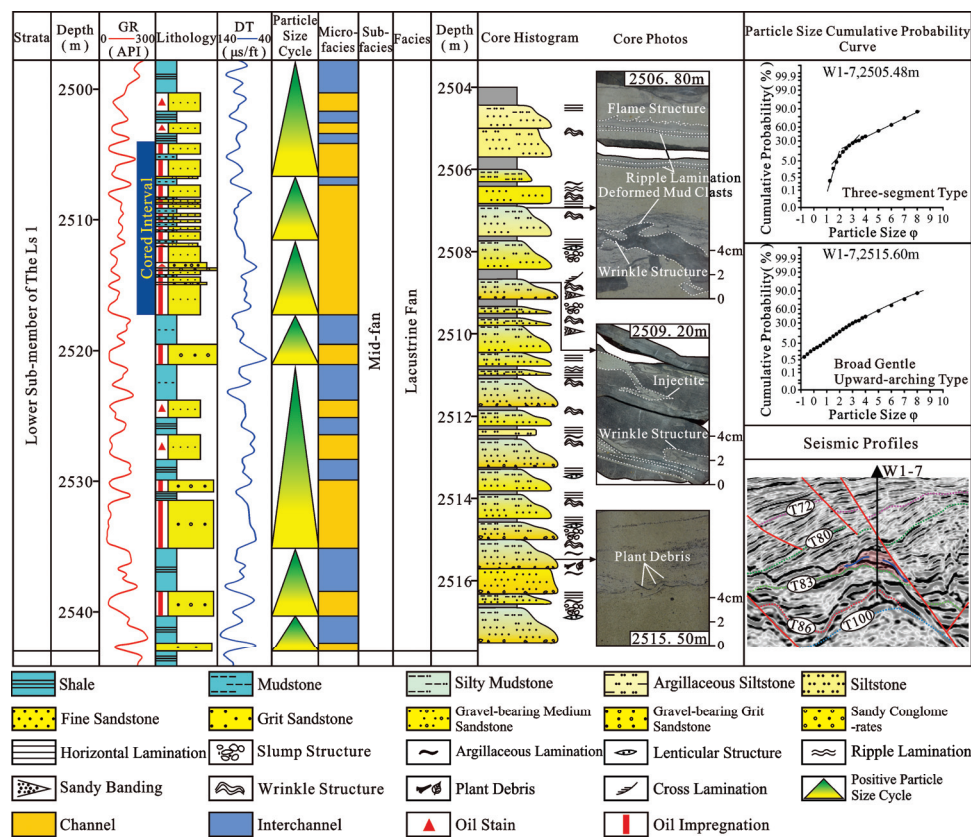


Figure 8. Characteristics of logging, core, sediment grain size, and cross-well seismic profile from Well W1-7.

2. Sedimentary Characteristics of Well W5-4

Well W5-4 is located on the middle part of the eastern slope of the Weixinan Low Uplift (Figure 1b). On the seismic profile, the Ls11 Sub-member in this well area generally presents a wedge-shaped sedimentary body with foreset reflection characteristics, and the interior shows medium-low frequency, weak amplitude, and weak continuity reflection features. Logging data indicate that the Ls11 Sub-member in this well has relatively fine particle size, mainly composed of interbedded fine sandstone, shale and mudstone. The GR curve is mainly finger-shaped or funnel-shaped.

The 1505.00–1512.56 m cored interval of Well W5-4 show that multiple reverse grain size cycles (coarsening-upward) were developed in the Ls11 Sub-member. The middle and lower parts of the cycles consist of fine sandstone and siltstone with massive structure; the sandstone contains gray-black argillaceous laminations and argillaceous bands, with parallel laminations and ripple laminations developed, and small-scale cross laminations locally visible. A small amount of gravel is found at the top of the cycles, with good sorting and rounding. The above sedimentary characteristics indicate that the Ls11 Sub-member in Well W5-4 developed a typical braided river delta river mouth bar microfacies.

3. Sedimentary Characteristics of Well W6-4

Well W6-4 is located on the lower part of the eastern slope of the Weixinan Low Uplift (Figure 1b). The 2190.50–2228.78 m cored interval of Well W6-4 show that the Ls13 Sub-member is mainly composed of mixed accumulations of brown sandy conglomerates and gray-black mudstone. The interface between sandy conglomerates and mudstone presents

a high-dip sliding surface, and a large number of slump structures, convolute laminations, and wrinkle structures are observed around the sliding surface. The cumulative probability curves of sediment grain size are mainly of the two-segment type, with particle sizes concentrated below 4Φ and small slopes of each component. The above sedimentary characteristics indicate that the Ls13 Sub-member in Well W6-4 mainly developed gravel-rich sublacustrine fans with typical gravity flow characteristics.

4.3.2. Connected Well Profile Sedimentary Characteristics

Connected well profiles are important means to reveal the spatiotemporal distribution and evolutionary laws of sedimentary systems. This research connected well profiles with multiple strikes in the study area were selected to conduct lateral correlation analysis of sedimentary systems. Research shows that during the Ls1 Member, sedimentary systems such as braided river deltas and sublacustrine fans were mainly developed in the study area, but their development characteristics vary significantly in different directions and different intervals. The following focuses on the detailed elaboration of the NE-trending connected well profile, which extends from the southern basin margin, passes through the northeastern slope of the Weixinan Low Uplift, and reaches Sub-sag B of the Weixinan Sag (Figure 9).

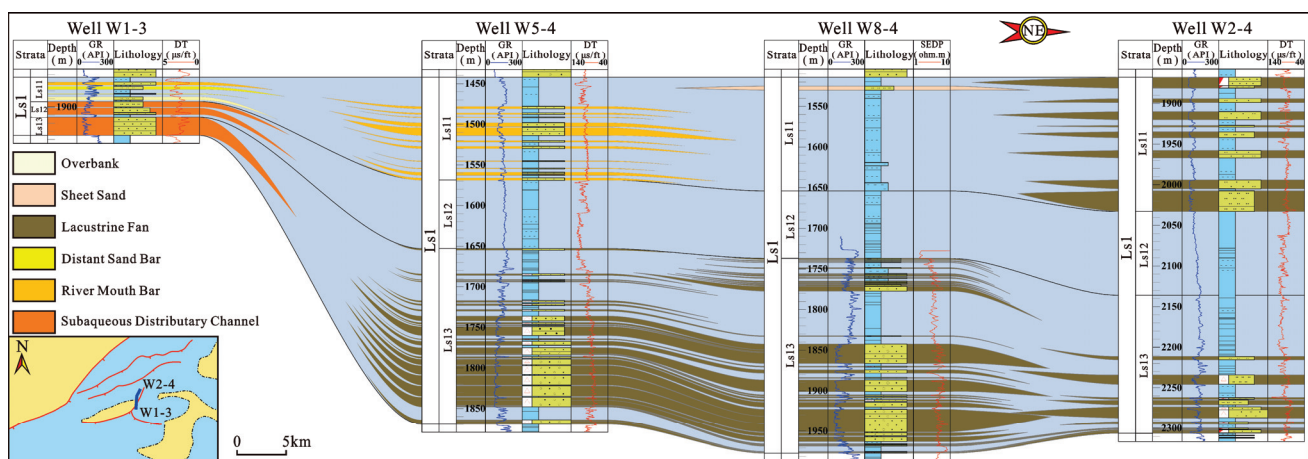


Figure 9. Well correlation profile of the Ls1 Member, from the southern basin margin to Sub-sag B, Weixinan Sag.

During the Ls13 Sub-member stage, the lithology of the lower interval of Well W1-3 (close to the southern basin margin) is dominated by thick-bedded fine sandstone, and the GR curve is mainly characterized by medium-amplitude serrated box shapes, which is inferred to be distributary channel deposits located on the flank of the main channel of the subaqueous distributary channel on the braided river delta front. The lithology of the lower interval of Well W5-4 (situated on the middle part of the eastern slope of the Weixinan Low Uplift) is dominated by sandy conglomerates, transitioning upward to mudstone interbedded with gravel-bearing medium sandstone; the lower part of the GR curve is mainly medium-high amplitude weakly serrated box shapes, while the upper part consists of low-amplitude serrated curves interspersed with finger shapes. For Well W8-4 (located on the middle-lower part of the eastern slope of the Weixinan Low Uplift), the lithology of the lower interval is dominated by gravel-bearing fine sandstone, and the upper interval is thick-bedded mudstone interbedded with thin-bedded gravel-bearing fine sandstone; the lower part of the GR curve is mainly medium-high amplitude serrated box shapes, and the curves corresponding to the sandstone in the upper interval are serrated bell shapes and finger shapes. As for Well W2-4 (located on the lower part of the eastern slope of

the Weixinan Low Uplift), the lithology of the lower interval is dominated by sand-mud interbeds with a very small amount of gravel, and the upper interval is mainly mud and shale deposits; the lower part of the GR curve is mainly finger-shaped, while the upper part is nearly flat or low-amplitude serrated curves. The above characteristics indicate that Wells W5-4, W8-4 and W2-4 all developed sublacustrine fans in a semi-deep/deep lake setting. Laterally, sediment grain size fines and sandbodies thickness decreases toward the basin center. Vertically, all three wells show upward-fining trends, indicating waning sediment supply, possibly with a late-stage pulse from local sources (e.g., Well W8-4).

In the Ls12 Sub-member stage, Well W1-3 is dominated by thin-bedded argillaceous siltstone and argillaceous fine sandstone, with particle size gradually becoming finer from bottom to top; the GR curve is medium-low amplitude serrated bell shapes, indicating the inherited development of subaqueous distributary channel deposits on the braided river delta front. Wells W5-4, W8-4, and W2-4 mainly develop thick-bedded mud and shale deposits, with nearly flat GR curves. The above characteristics indicate that the sediment supply capacity was extremely weak during this period, and only small-scale braided river delta deposits were developed in areas near the basin margin.

During the Ls11 Sub-member stage, Well W1-3 is dominated by argillaceous siltstone, fine sandstone, and mudstone, with particle size gradually becoming coarser from bottom to top; the overall GR curve is funnel-shaped, indicating the development of river mouth bar and distant sand bar microfacies on the braided river delta front. The lower part of Well W5-4 is dominated by mud and shale, with a gradual increase in fine sandstone upward; the GR curve gradually changes from nearly flat in the lower part to multiple superimposed funnel shapes in the upper part, thus inferred to be river mouth bar deposits on the braided river delta front. Well W8-4 is mainly composed of mud and shale, with thin-bedded argillaceous siltstone interbedded at the top, thus inferred to be sheet sand deposits in the prodelta. Well W2-4 is mainly composed of mudstone interbedded with siltstone and fine sandstone; the GR curve is a superposition of bell shapes and serrated box shapes, showing typical sublacustrine fan characteristics. The above characteristics indicate that multi-layer fine sandstone deposits supplied by a new source area appeared on the middle part of the slope (Well W5-4 area), which is inferred to possibly come from the Weixinan Low Uplift. Clastic materials were transported northeastward along the eastern slope of the Weixinan Low Uplift, developing a braided river delta on the middle part of the slope and sublacustrine fans on the lower part of the slope.

5. Discussion

5.1. Activity of Fault 3 and Tectonic Evolution of the Weixinan Low Uplift

For continental rift basins, the activity of their main faults not only shapes the tectonic framework of the basin, but also directly controls the development and evolution of secondary tectonic units [51,52]. Regarding studies on the evolution of normal faults in an extensional tectonic setting, the academic community has established two classic growth models based on the spatiotemporal coupling between the lateral extensional length and vertical displacement of faults, namely the isolated fault growth model and the constant-length fault growth model [53–57].

As the major boundary fault separating the Weixinan Sag and the Haizhong Sag, the evolution of Fault 3 has long been a research focus. Li et al. [58] stated that Fault 3 exhibited typical segmented activity characteristics during the paleogene depositional stage: temporally, it showed an evolutionary pattern of strong activity during the Liushagang Formation depositional stage and weak activity during the Weizhou Formation depositional stage; spatially, the activity intensity of the eastern segment was significantly higher than that of the western segment. Zhang et al. [15] and Zheng and Ge [59] suggested that Fault 3

was basically undeveloped or only experienced weak activity during the depositional stage from the Changliu Formation to the Liushagang Formation. During the depositional stage of the Weizhou Formation, the intense activity of Fault 3 directly resulted in the strong tilted uplift of the Weixinan Low Uplift. Zhang et al. [20] argued that the tilted structural geometry of the Weixinan Low Uplift, which was characterized by a gentle northern slope and a steep southern slope, and its development and tectonic evolution were mainly controlled by Fault 3. Li et al. [18] proposed that Fault 3 is an inherited boundary fault that initiated in the initial rifting stage, and underwent continuous extensional activity throughout the depositional stage of the Liushagang Formation. Hu et al. [35] concluded that Fault 3 had roughly reached its ultimate constant length in the initial active stage, and its subsequent evolution was dominated by the continuous increase in vertical displacement.

Based on the quantitative analysis of the paleo-throw of Fault 3 and the reconstruction results of the tectonic paleogeomorphology of the Weixinan Low Uplift and its surrounding areas, this study suggests that Fault 3 mainly follows the isolated fault growth model during its evolution. The evolutionary process shows that Fault 3 was nearly inactive during the depositional stage of the Ls2 Member, and only initiated activity gradually during the depositional stage of the Ls13 Sub-member, thereby controlling the tectonic evolution of the Weixinan Low Uplift.

5.2. “Source-to-Sink” Evolution of the Weixinan Low Uplift and Its Surrounding Areas

The dynamic evolution of tectonic paleogeomorphology is a key factor controlling the evolution of source systems, the transition of sediment transport pathways, and the spatiotemporal distribution of sedimentary systems, thereby exerting a critical impact on the evolution of “source-to-sink” systems [1,47,60,61]. Numerous studies on continental rift basins have demonstrated that the dynamic changes in the geomorphology and spatial distribution of intrabasinal low uplifts directly restrict the development and evolution of their peripheral “source-to-sink” systems. In particular, when a low uplift is gradually uplifted from subaqueous to subaerial conditions, its attribute changes from a sink area to a source area, thereby completely reshaping the “source-to-sink” systems in its periphery [6,8,9].

As an important tectonic unit in the Northern Depression of the Beibuwan Basin, the “source-to-sink” system of the Weixinan Low Uplift and its surrounding areas has long attracted the attention of scholars. Liu et al. [62] suggested that during the depositional stage of the Liushagang Formation, only local highs of the Weixinan Low Uplift were exposed and eroded, resulting in limited overall provenance supply capacity that could not develop large-scale and continuous clastic supply, and the clastic sediments on the peripheral sags were mainly derived from extrabasinal large-scale uplift areas. Zhang et al. [20] and Jin [63] argued that the Weixinan Low Uplift was only exposed subaerially during the depositional stage of the Ls3 Member and the Ls1 Member, and could act as an effective provenance to supply clastic sediments to the peripheral sags. In contrast, during the depositional stage of the Ls2 Member, the Weixinan Low Uplift was entirely submerged subaqueously and did not possess the geological conditions for sediment supply. Li et al. [18] proposed that the Weixinan Low Uplift was developed in the initial rifting stage, remained in an exposed and denudational state throughout the depositional stage of the Liushagang Formation, and could provide stable clastic sediment supply to the peripheral sags. Liu [16] concluded that the Yuegui Uplift, Qixi Uplift, and Weixinan Low Uplift all supplied clastic sediments to the eastern sag adjacent to the Weixinan Low Uplift during the depositional stage of the Ls1 Member, and sediments from different sources were superimposed in the center of the sag.

Through the analysis of the spatiotemporal evolution of the “source-to-sink” system and sedimentary systems in the Weixinan Low Uplift and its surrounding areas, this study

reconstructed the dynamic evolutionary processes of the “source-to-sink” system in the study area. The results show that the study area was mainly supplied by two major extrabasinal source areas during the Ls2 Member stage, namely the Yuegui Uplift and the Qixi Uplift. In this period, the lake basin had a large extent due to the regional lake transgression, while the supply capacity of extrabasinal source areas was weak, resulting in a short transport distance of clastic sediments. The clastic sediments were mainly concentrated and distributed adjacent to the basin margin. In the Ls13 Sub-member stage, the clastic supply capacity of the extrabasinal source areas was enhanced. Clastic sediments supplied by the central provenance of the Qixi Uplift were transported and deposited northeastward along the transfer zone developed between the eastern and western segments of Fault 3. In the Ls12 Sub-member stage, the clastic supply capacity of the extrabasinal source areas was slightly weakened compared with the Ls13 Sub-member stage. At this time, the transport pathway of clastic sediments from the central Qixi Uplift provenance was blocked by the gradually uplifting subaqueous Weixinan Low Uplift. The sediments were only deposited on the hanging wall of the eastern segment of Fault 3 due to the deflection of sediment transportation direction. In the Ls11 Sub-member stage, the Weixinan Low Uplift was exposed subaerially, became a significant intrabasinal source area, and began to supply clastic sediments to its eastern and northern margins, thus altering the overall “source-to-sink” systems and the spatiotemporal distribution of sedimentary systems in the study area.

5.3. Spatiotemporal Distribution and Evolutionary Characteristics of Sedimentary Systems

Integrating the analysis of sedimentary characteristics from single wells and well correlation profiles, detailed interpretation of high-precision 3D seismic data, and the results of the “source-to-sink” process analysis, this research precisely depicted the spatiotemporal distribution and evolutionary characteristics of sedimentary systems in the Weixinan Low Uplift and its surroundings during the depositional stage of the Ls2 Member and Ls1 Member. Research shows that the evolution of the “source-to-sink” systems (including source areas, sediment transport pathways, etc.) and sedimentary systems in the Weixinan Low Uplift and its surroundings are obviously affected by the activity of Fault 3 and the associated paleogeomorphology changes.

During the Ls2 Member stage, Fault 3 was not yet active, and the study area (the original region of Weixinan Low Uplift development) was characterized by gently inclined subaqueous slope. Semi-deep/deep lake facies were widely distributed in the basin to the north of subaqueous slope (Figure 10a). In this period, clastic materials in the study area were mainly derived from the Yuegui Uplift and Qixi Uplift. The sediments from the Yuegui Uplift were supplied towards southward and southeastward directions, mainly accumulating at the roots of basin-boundary faults (e.g., Weixinan Fault, Fault 1) and developing small-scale fan deltas. The sediments from the Qixi Uplift advanced northward along the gently inclined subaqueous slope, developing small-scale braided river deltas, with small-scale sublacustrine fans developed at the front of the deltas on the middle-lower part of the slope (Figure 11d).

During the Ls13 Sub-member stage, Fault 3 initiated in a segmented manner, with the Weixinan Low Uplift developing a subaqueous embryonic structure and the Eastern Sub-sag of the Haizhong Sag developing synchronously. During this period, the study area was still mainly supplied by the source areas of the Yuegui Uplift and Qixi Uplift. The sediments from the Yuegui Uplift mainly accumulated in the northwestern and northern parts of the study area, developing fan deltas in an inherited manner, with a significant increase in overall scale. The underwater development of the Weixinan Low Uplift altered basin paleogeomorphology, which gradually deflected the transport direction of clastic material

from the central Qixi Uplift, developing a braided river delta extending northeastward (Figures 10b and 11c). At the front of the braided river delta, controlled by the activity of Fault 3 and the topography of the underwater low uplift, gravel-rich sublacustrine fans (e.g., Well W5-4 area) dominated by coarse-grained sediments were developed on the middle-lower part of the slope, while sand-rich sublacustrine fans (e.g., Well W8-4 area) were developed on the lower part of the slope (e.g., Sub-sag B, Sub-sag 11). In addition, sediments from the eastern part of the Qixi Uplift continued to be supplied northward, developing braided river deltas in an inherited way, with large-scale sublacustrine fans developed at their front (Figure 10b).

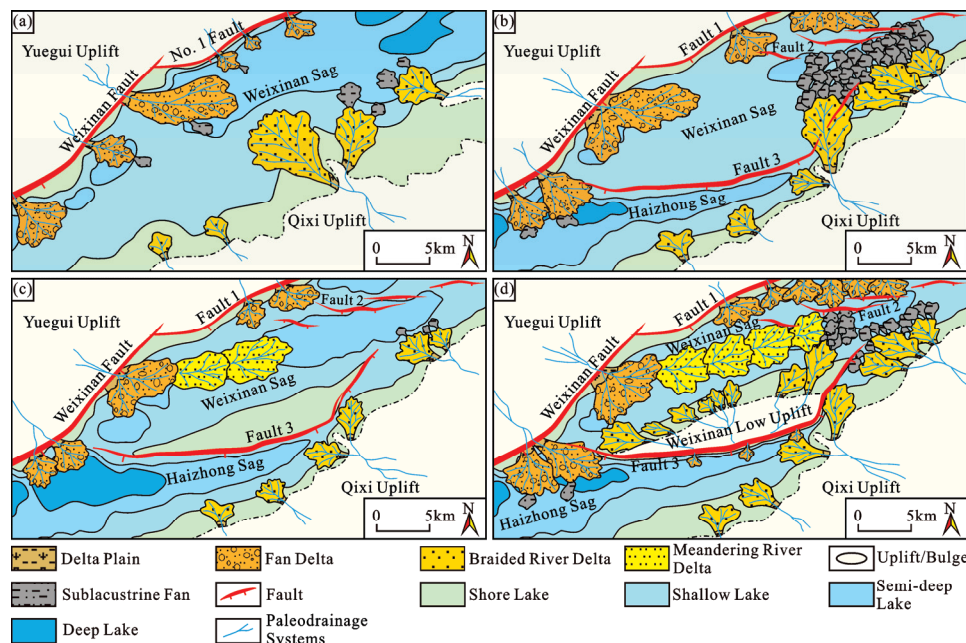


Figure 10. Distribution of sedimentary facies in different sedimentary periods of the Weixinan Low Uplift and its surrounding areas. (a) Ls2 Member. (b) Ls13 Sub-member. (c) Ls12 Sub-member. (d) Ls11 Sub-member.

During the Ls12 Sub-member stage, Fault 3 continued to be active and gradually connected, and the low uplift further uplifted underwater and expanded in scale; at the same time, the Eastern Sub-sag of the Haizhong Sag deepened and widened. During this period, accompanied by lacustrine transgression, the distribution range of semi-deep/deep lake facies expanded. The sediments from the Yuegui Uplift continued to develop fan deltas at the northwestern and northern basin margins of the study area, with a significant reduction in overall scale (Figure 10c). The sediments supplied by the central part of the Yuegui Uplift developed a fan delta on the hanging wall of the western segment of the Weixinan Fault; affected by the lacustrine basin floor topography, the sediments continued to advance eastward and gradually evolved into meandering river delta deposits. Under the combined influence of the subaqueous uplift of the low uplift and the expansion of the Eastern Sub-sag of the Haizhong Sag, nearly all sediments from the central Qixi Uplift were trapped, with only a small amount escaping interception, and only small-scale braided river deltas were developed at the edge of the Eastern Sub-sag of the Haizhong Sag (Figure 11b). In addition, a small amount of sediments from the eastern part of the Qixi Uplift were supplied northward, developing small-scale braided river deltas, with small-scale sublacustrine fans developed at their front (Figure 10c).

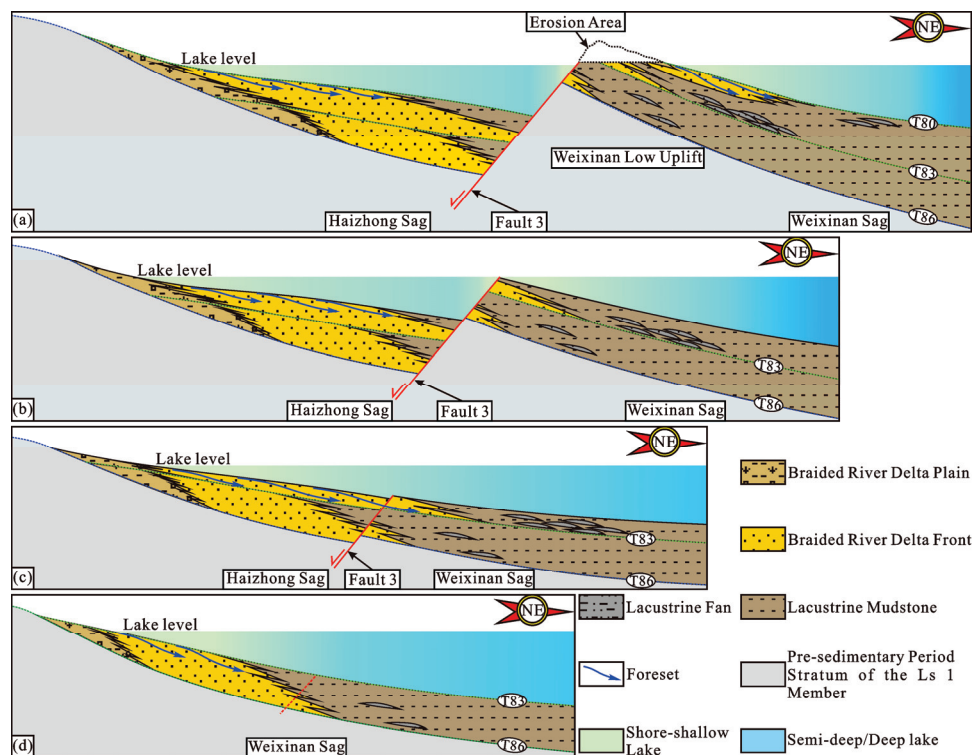


Figure 11. Tectono-sedimentary models for different periods of the Weixinan Low Uplift. (a) Ls11 Sub-member depositional stage. (b) Ls12 Sub-member depositional stage. (c) Ls13 Sub-member depositional stage. (d) Ls2 Member depositional stage.

In the Ls11 Sub-member stage, Fault 3 became more intensely active, causing the Weixinan Low Uplift to eventually uplift and expose above the water surface, and then gradually undergo erosion, thus becoming a new intrabasinal source area. During this period, the Yuegui Uplift and Qixi Uplift still continuously supplied sediments into the lake basin in an inherited manner. Affected by the enhanced source supply capacity, the scale and scope of fan deltas and meandering river deltas developed on the northern part of the study area increased significantly, leading to the re-transport of sediments at the front of the deltas and their final arrival at the sag centers (e.g., Sub-sag A, Sub-sag B), where multiple sets of superimposed sublacustrine fans formed by the convergence of multi-directional sources were developed (Figure 10d). At the same time, due to the influence of topographic differences around the Weixinan Low Uplift, sediments from the Weixinan Low Uplift were mainly transported to the gentle slope belts on the eastern, western, and northern sides of it, developing large-scale braided river deltas (Figure 11a). In contrast, fewer sediments were supplied to the steep slope belt on the southern side of the Weixinan Low Uplift, where only a small number of small-scale fan deltas were developed. In addition, the scale and scope of the braided river delta developed by the northward supply of sediments from the eastern part of the Qixi Uplift also increased significantly, with small-scale sublacustrine fans developed in the sag areas at its front (e.g., Sub-sag B, Sub-sag 11).

6. Conclusions

1. Quantitative analysis of fault activities demonstrates that the evolution of Fault 3 followed the isolated fault growth model during deposition of the Liushagang Formation, and was the fundamental factor governing the evolution of the tectono-sedimentary framework of the Weixinan Low Uplift and its surrounding regions. During the Ls2 Member deposition stage, Fault 3 remained inactive, and the study area was manifested as a gently dipping subaqueous slope which extending towards the

northern deep lake. During the Ls1 Member stage, the growth of Fault 3 underwent an evolutionary process of initial segments, gradual linkage, and intense activity, which drove the uplift and subaerial exposure of the Weixinan Low Uplift, and separated the previously unified lacustrine basin into the Weixinan Sag and Haizhong Sag.

2. Reconstruction of the “source-to-sink” systems in the Weixinan Low Uplift and its surrounding areas reveals that clastic sediments in the study area were dominantly supplied by extrabasinal source areas (the Yuegui Uplift and Qixi Uplift) from the Ls2 Member stage to the Ls12 Sub-member stage. In the Ls11 Sub-member stage, the Weixinan Low Uplift was subaerially exposed, subjected to denudation, and evolved into a critical intrabasinal source area which governed the evolution of the “source-to-sink” system and sedimentary systems in the study area together with the extrabasinal source areas (the Yuegui Uplift and Qixi Uplift).
3. The spatiotemporal distribution of sedimentary systems in the study area was characterized by distinct response to the evolution of tectonic paleogeomorphology and “source-to-sink” systems. Prior to the Ls1 Member deposition, fan deltas were developed along the northern and northwestern margins of the Weixinan Sag, while braided river deltas were developed along the southern margin. In the Ls13 Sub-member stage, the Weixinan Low Uplift initiated subaqueous development and deflected the transport direction of clastic sediments which were derived from the central part of the Qixi Uplift, resulting in the development of large-scale lacustrine fans in the eastern subsag centers adjacent to the Weixinan Low Uplift. In the Ls11 Sub-member stage, the Weixinan Low Uplift was subaerially exposed and began to supply clastic sediments to the surrounding subsags. Braided river delta systems were developed on the gentle slope belts along its eastern, western and northern margins, lacustrine fan deposits were deposited in the lower part of the eastern gentle slope belt, and small-scale fan delta systems were developed along the southern steep slope belt.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse14060554/s1>, Figure S1: The tectonic paleogeomorphology of the Weixinan Low Uplift and its surrounding areas during the Ls3 Member; Figure S2: Representative core photographs.

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