

Article

Identification Characteristics of Interlayers and Interbeds in Shoreface Reservoirs and Their Influence on Remaining Oil Distribution—A Case Study of the Donghe Sandstone in the Hudson Oilfield

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Abstract

The Donghe Sandstone in the Tarim Basin represents marine littoral deposits. Cyclical variations in hydrodynamic conditions during sedimentary evolution led to the widespread development of intercalations/interbeds within the reservoir, which directly impact hydrocarbon development. It is imperative to elucidate the genesis, types, and distribution of these intercalations, and to reveal their controlling effect on residual oil. Based on detailed core observations, the genesis and classification of interbeds in the study area were determined. A three-dimensional cross-plot method was employed to establish interbed identification criteria, and architectural element analysis was used to predict their spatial distribution. Results indicate that interbeds in the study area can be classified into muddy interbeds, calcareous interbeds, and calcareous-muddy interbeds. The heterogeneity of interlayer and intralayer interbeds and sand body connectivity were systematically characterized. This enabled the prediction of distribution patterns and styles of different interbeds within the coastal-plain reservoir, as well as the relationship between residual oil and interbeds. Production practice shows that residual oil is mainly distributed in high-position well areas. This solves the problem of declining reservoir production in the Hudson Oilfield caused by interbed distribution and provides a reference for predicting residual oil distribution in marine coastal sedimentary oilfields.

Keywords: Tarim Basin; Donghe sandstone; Hudson oilfield; reservoir configuration; coastal phase; intercalation; residual oil



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1. Introduction

Barriers and intercalations, developed within reservoirs, are impermeable or relatively low-permeability layers. Based on their distribution continuity and spatial scale, they can be classified into barriers and intercalations [1]. Barriers are generally broadly distributed and laterally stable, effectively blocking and controlling fluid flow; thus, they serve as a crucial geological basis for subdividing development intervals and determining water injection patterns [2]. Conversely, intercalations are smaller in scale and laterally discontinuous, primarily exerting localized impacts on fluid seepage paths within individual flow units. This often leads to uneven water sweep efficiency and the formation of remaining oil enrichment zones [3]. Field production practices have demonstrated that the presence of barriers and intercalations significantly intensifies reservoir heterogeneity, resulting in

deteriorated waterflooding performance and obscuring the distribution patterns of remaining oil [4]. Particularly in the context of widely developed shoreface sandstones, where the sand bodies inherently exhibit pronounced heterogeneity, the internal development of barriers and intercalations further exacerbates this phenomenon. This degrades sand body connectivity and creates flow barriers, ultimately reducing water drive efficiency and acting as the core limiting factor for characterizing remaining oil distribution and tapping its potential [5].

Reservoir heterogeneity is one of the core characteristics of clastic reservoirs, and its degree directly determines hydrocarbon enrichment patterns and development performance. However, significant differences exist in the heterogeneity characteristics between continental and marine clastic reservoirs [6]. Influenced by factors such as the limited distribution range of sedimentary facies, rapid lateral facies variations, and unstable sediment supply, continental clastic sequences exhibit pronounced reservoir heterogeneity. Furthermore, their reservoir types and spatial distribution patterns are complex, making them a focal point of reservoir research for many years [7]. In contrast, marine clastic sequences are subjected to significant wave winnowing; thus, their reservoirs often feature relatively homogeneous lithology and excellent lateral continuity. They typically possess a high quartz content and low clay mineral content, corresponding to high levels of both compositional and textural [8]. The Hudson Oilfield is China's first massive, continuous marine sandstone oilfield with reserves exceeding 100 million tons, and its main producing zone is the shoreface Donghe Sandstone. The Donghe Sandstone is not only a typical large-scale marine sandstone reservoir formed under deep-burial and complex tectonic backgrounds, but it also experienced multiple, frequent transgression-regression cycles during its geological evolution, preserving highly representative depositional records of unbarred, wave-dominated shoreface facies internally [9]. This unique sedimentary hydrodynamic setting causes the genetic mechanisms and distribution patterns of its internal barriers and intercalations to differ significantly from those of conventional continental reservoirs. Therefore, utilizing it as a research target area holds significant representative and unique value for revealing the heterogeneity patterns of marine shoreface reservoirs. Multiple types of barriers and intercalations are developed within this interval. Production dynamics indicate that they not only directly affect reservoir storage properties but also exert critical control over fluid flow processes within the reservoir. In the context of widespread shoreface sandstones, the sand bodies exhibit pronounced heterogeneity. The barriers and intercalations developed within these sand bodies further exacerbate this reservoir heterogeneity, leading to deteriorated sand body connectivity, the formation of flow barriers, and a reduction in water sweep efficiency. Existing research on predicting barriers and intercalations predominantly focuses on continental clastic depositional environments, such as fluvial and deltaic facies [10], whereas studies on the internal barriers and intercalations within shoreface marine sandstone reservoirs remain relatively scarce. Traditional views posit that shoreface depositional environments are subjected to repeated wave winnowing, resulting in sand bodies with high compositional maturity and excellent lateral continuity [11]; thus, the development of barriers and intercalations is considered limited. However, development practices in the Donghe Sandstone of the Hudson Oilfield have demonstrated that multiple types of barriers and intercalations can indeed develop within shoreface reservoirs, and they play a crucial role in controlling reservoir connectivity, waterflooding sweep efficiency, and the distribution of remaining oil [12]. Nevertheless, current research on barriers and intercalations in shoreface marine sandstone reservoirs characterized by deep burial and complex tectonic backgrounds—such as the Donghe Sandstone in the Tarim Basin—still faces prominent issues. These include insufficient research depth, poor adaptability of technical methods, and a lack of tight integration with efforts

to tap remaining oil potential. Previous studies have primarily focused on describing the basic characteristics of barriers and intercalations, failing to fully account for the unique shoreface depositional environment of the study area or to systematically reveal the intrinsic relationships among the genesis and spatial distribution of barriers and intercalations and the distribution of remaining oil. Consequently, these studies struggle to effectively guide efficient reservoir development and the practical exploitation of remaining oil.

To address the aforementioned issues, this study focuses on the shoreface reservoirs of the Donghe Sandstone in the Tarim Basin. Utilizing multi-source data—including cores, well logs, and development dynamics—we precisely characterize the distribution, lithological features, and logging responses of the barriers and intercalations within these shoreface reservoirs, and establish tailored identification criteria for the study area. The genetic mechanisms are systematically analyzed to clarify the controlling roles of sedimentation and diagenesis on the development of these impermeable layers. Furthermore, the influence of internal barriers and intercalations on remaining oil distribution is thoroughly investigated to reveal the enrichment mechanisms of remaining oil under their control. The unique contribution of this work lies in addressing the current research deficiencies regarding barriers and intercalations in marine shoreface sandstone reservoirs and refining the corresponding technical methodologies. Specifically, this study highlights the differences in formation mechanisms and identification approaches between shoreface and continental reservoirs. It advances the research from mere “qualitative description” to an integrated analytical framework of “identification criteria–architectural constraints–development response.” This work provides a methodological reference for remaining oil prediction and fine-scale potential tapping during the high-water-cut stage of marine shoreface reservoirs, while directly coupling the study of barriers and intercalations with development dynamics.

2. Geological Overview

The Hudson Oilfield is located in the Manjiaer Depression-Hudson Tectonic Zone of the Tarim Basin (Figure 1a–c), representing a low-amplitude anticlinal structure developed against the background of a structural nose [13]. Its most representative Carboniferous Donghe Sandstone reservoir is characterized by deep burial, low structural amplitude, an extensive oil-bearing area, thin reservoir thickness, and low reserve abundance [14]. The reservoir physical properties are overall dominated by medium to high porosity and permeability; the porosity primarily ranges from 12% to 24%, and the permeability ranges from $<1 \times 10^{-3} \mu\text{m}^2$ to $2000 \times 10^{-3} \mu\text{m}^2$. This reservoir is a composite stratigraphic-structural reservoir with a tilted oil-water contact (OWC), featuring complex reservoir characteristics that belong to unbarred, wave-dominated sandy shoreface deposits. The top and bottom of the main pay zone are both bounded by unconformities, overlain by a stable middle mudstone interval and underlain by Silurian tight sandstones. The Donghe Sandstone reservoir has a small thickness and is distributed in a strip-like pattern along the coastline, gradually thinning and pinching out from southwest to northeast. While shoreface reservoirs in most areas only develop a small number of thin argillaceous intercalations, the Donghe Sandstone interval in the Hudson Oilfield develops an abundance of argillaceous barriers and intercalations. During its depositional evolution, the study area experienced frequent transgression-regression cycles [15]. These cyclic sea-level fluctuations resulted in the regular alternation of hydrodynamic conditions. During transgressions or periods of weakened hydrodynamics, wave winnowing diminished, and fine-grained argillaceous and carbonate materials settled and cemented in low-energy environments [16], forming widely distributed argillaceous and calcareous barriers and intercalations. Conversely, during regressions or under high-energy conditions, coarse-grained sand bodies were deposited again. This periodic variation in sedimentary hydrodynamics is the fundamen-

tal cause for the development of multi-stage and multi-type barriers and intercalations within the study area. Furthermore, the continuous action of late-stage tectonic stresses caused severe deformation of the sand bodies, generating abundant argillaceous barriers and intercalations, which constrained the distribution of remaining oil. Centimeter-scale calcareous and calcareo-argillaceous barriers and intercalations are commonly developed within the reservoir, significantly enhancing reservoir heterogeneity [17]. Influenced by the internal architecture of the beach bars and the distribution of barriers and intercalations, flow barrier interfaces and medium- to high-permeability interconnected channels are developed within the beach bars, which restrict the distribution of remaining oil and affect the effective development of the reservoir. At present, the comprehensive water cut of the reservoir has exceeded 80%, marking its entry into the medium- to high-water-cut stage. During this stage, water injection efficiency is relatively low, and development becomes highly challenging.

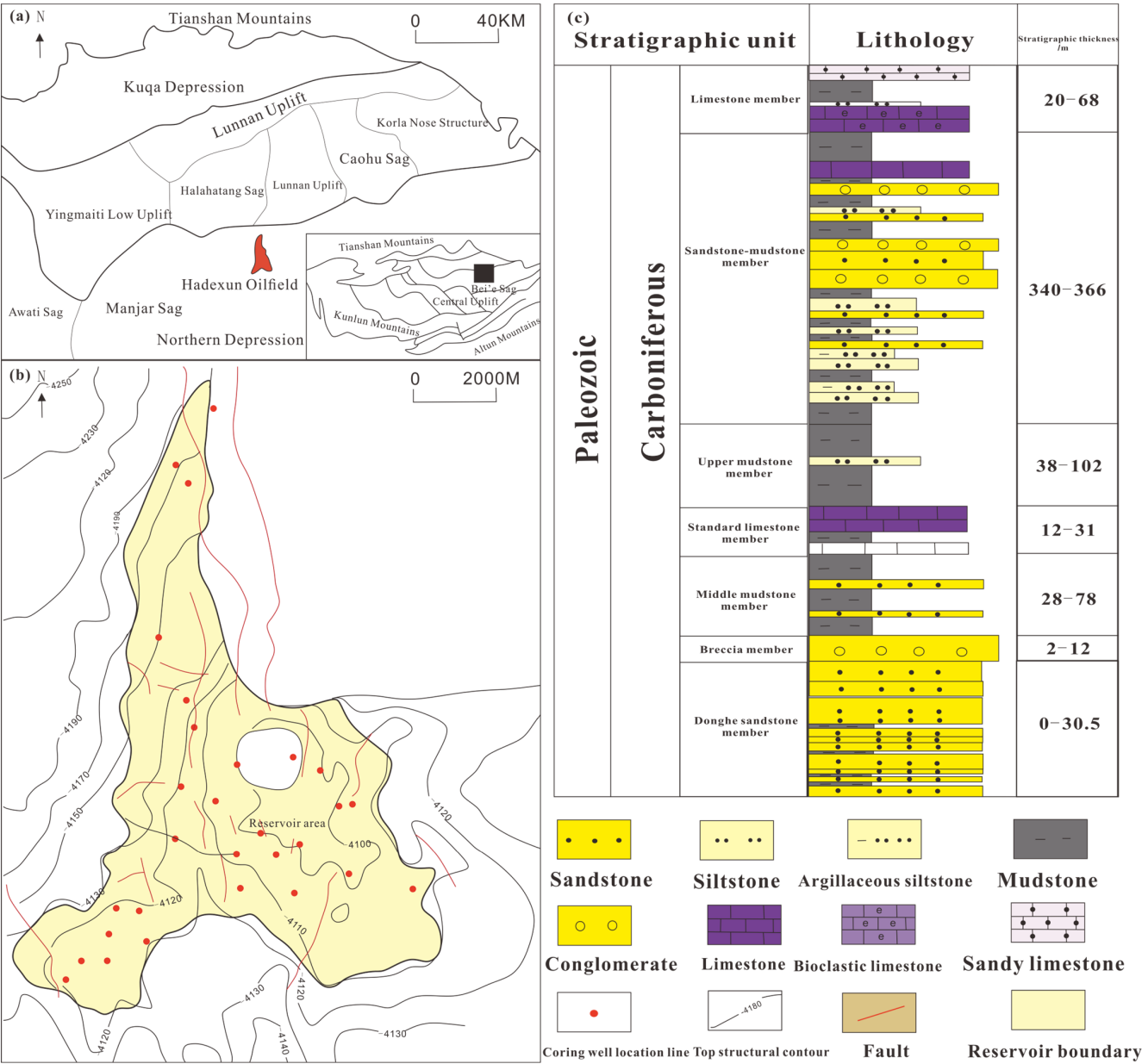


Figure 1. Hudson Regional Distribution Map. (a) Tectonic characteristics of the northern Tarim Basin and the structural location of the Hudson Oilfield; (b) Structural map of the top surface of the Donghe Sandstone in the Hudson Oilfield; (c) Stratigraphic column of the study area.

3. Materials and Methods

3.1. Shore-Adjacent Reservoir Characteristics
3.1.1. Sedimentary Facies Characteristics

For the high-resolution characterization of internal heterogeneity in shoreface reservoirs, this study integrates architectural element analysis theory with marine shoreface depositional hydrodynamics [18,19]. Within the Donghe Sandstone reservoir, four types of fifth-order architectural elements and their spatial configurations were identified. The sedimentary facies in the study area transition landward from the shoreface, through the foreshore and backshore, to the coastal dune subfacies. Based on structural characteristics, each subfacies is further subdivided into three types of fourth-order microfacies: beach, bar, and trough. Furthermore, the fourth-order architectural elements are categorized into two types of third-order elements—barriers and intercalations—according to their sealing effects on remaining oil. Detailed dissection in areas with dense well patterns confirms that the calcareous and calcareo-argillaceous barriers and intercalations in the study area are primarily controlled by fifth-order architectural boundaries and fourth-order internal lateral accretion surfaces. Given the restricted distribution of the backshore and coastal dune subfacies, this paper focuses on investigating the impact of the shoreface and foreshore depositional systems on the development of barriers and intercalations (Figure 2). (The core data was obtained from Yangtze University, China).

GR Morphology				DEN Morphology		Potential Depositional Environments	Representative Core Photographs
Primary Order		Secondary Order					
Serrated funnel-shaped		Bell-shaped		Box-shaped		Inner bar wing	5127.22  Inner bar wing 5126.43  Outer bar wing Bar core 5128.15
		Box-shaped				Bar core	
		Funnel-shaped				Outer bar wing	
Low-amplitude box-shaped		Linear		Bell-funnel shape		Shoal	
High-amplitude finger-shaped		Bell-funnel combination		Finger-shaped		Trough	5089.48  Trough 5090.23  Inner bar wing Trough

Figure 2. Common GR Curve Patterns in Donghe Sandstone and Their Indicated Sedimentary Environments.

- (1) Shoreface subfacies: This subfacies occurs within the wave-agitated zone between the normal wave base and the mean low-tide level and is subdivided into three architectural microfacies based on hydrodynamic variations: shoreface sand sheet, shoreface bar, and shoreface trough. The shoreface sand sheet is characterized by frequently fluctuating hydrodynamics, with a medium- to high-amplitude serrated bell- or funnel-shaped GR curve (40–60 API). The shoreface bar exhibits decreasing hydrodynamic energy, marked by a medium-amplitude box-shaped GR pattern (35–50 API). The shoreface trough is distinguished by alternating high- and low-energy conditions, showing a high-amplitude serrated funnel-shaped or chaotic GR response.

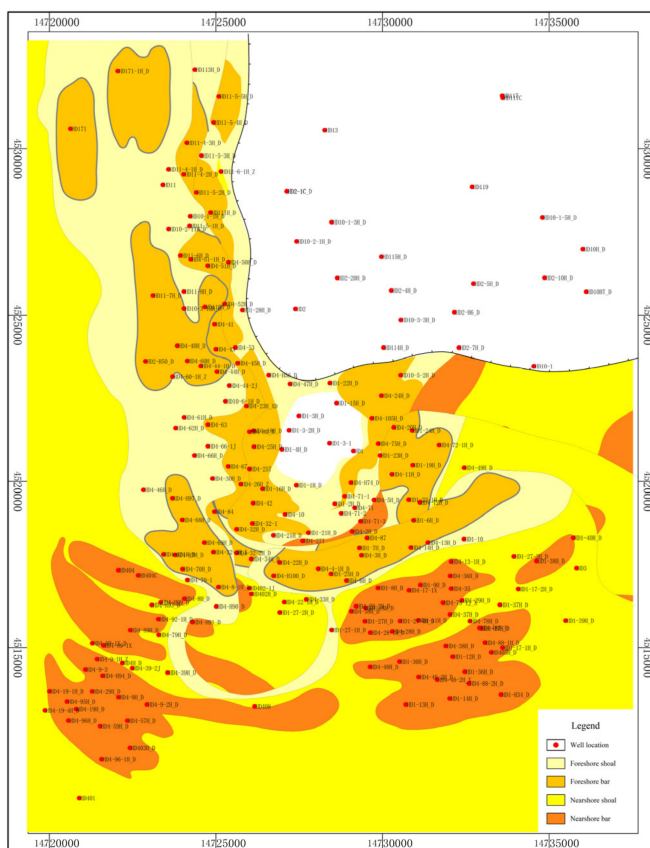
- (2) Foreshore subfacies: This subfacies occurs within the surf zone and is governed by strong wave dynamics. It is subdivided as follows: 1. Foreshore sand sheet, characterized by uniform grain size and a low-amplitude serrated box-shaped or finger-like GR pattern; 2. Foreshore bar, subjected to intense wave reworking and sorting, displaying a low-amplitude, gently box-shaped GR pattern with values concentrated between 22 and 35 API; and 3. Foreshore trough, a low-energy depositional area with thin sand-mud interbeds, exhibiting a medium-amplitude serrated bell-shaped GR curve.

3.1.2. Sedimentary Facies Distribution Patterns

Controlled by the central uplift belt, the Donghe Sandstone in the study area exhibits distinct differential sedimentary characteristics: the strata are primarily developed on the western flank in the north, whereas they extend across both sides of the uplift in the south [20]. The primary reservoirs consist of the CIII-3S-6S sub-members, which are distributed in sheet-like geometries along the paleocoastline. Their thickness, governed by hydrodynamic intensity, gradually thins landward, with multiple localized depocenters occurring within the CIII-4S-6S units. Vertical facies succession reveals an evolution from shoreface bar sands at the base to foreshore sand bodies in the middle and upper sections, which were influenced by high-energy wave and tidal regimes. These later deposits are characterized by coarser grain sizes and superior sorting and roundness. With increasing transgressive intensity, the shorezone retreated landward, restricting the accommodation space for beach sands and causing the depocenters to migrate seaward toward the open sea [21]. The overall hydrodynamic energy follows a systematic spatial distribution: it is highest in the western foreshore zone, followed by the interbedded bar-beach zone on the east, and lowest along the margin of the uplift (Figure 3a).

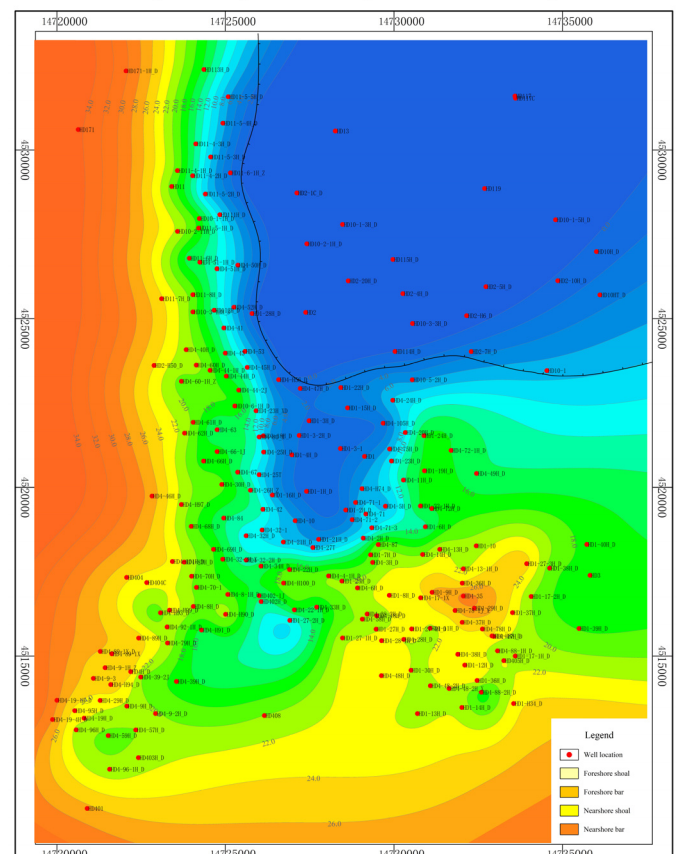
Furthermore, calcareous and calcareo-argillaceous impermeable barriers and interlayers are extensively developed within the reservoir, exhibiting prominent “filling-and-leveling” sedimentary features. In plan view, the study area features strip-like calcareous and calcareo-argillaceous interlayers that strike parallel to the paleocoastline, with an average width of approximately 126 m and a maximum lateral extent of 2 km. These interlayers are predominantly concentrated in back-bar beach and bar-wing settings. Vertically, the stacking of shoreface sandbars is frequently accompanied by argillaceous barriers and abrupt physical property change surfaces. Influenced by the periodic waning of hydrodynamic energy, diffuse flow processes during the terminal stages of sandbar deposition facilitated the accumulation of fine-grained materials, resulting in interlayer interfaces with high mud content. The sedimentary sequence demonstrates an upward-coarsening trend, characterized by improved sorting and roundness and a progressive decrease in mud content. Within an individual sandbar, the depositional energy at the bar core is significantly higher than at the bar wings. The spatial distribution of these barriers and interlayers is governed by sandbar stacking surfaces, facies transition surfaces, and microfacies transition zones; their thickness is positively correlated with the degree of abruptness in sedimentary energy fluctuations (Figure 3b).

Sedimentary Facies Planar Distribution of the CIII-3S-6S Interval



(a)

Isopach Map of the Donghe Sandstone Body



(b)

Figure 3. Thickness Map of CIII3S-7S Sand Body in the Study Area. (a) Sedimentary Facies Planar Distribution of the CIII-3S-6S Interval; (b) Isopach Map of the Donghe Sandstone Body.

3.2. Types and Distribution of Barriers and Interlayers

Based on their distribution scale and fluid regulation capacity, this study classifies the impermeable layers within the reservoir into barriers and interlayers (baffles) [22]. Barriers, ranging in thickness from tens of centimeters to tens of meters, are widely distributed and exhibit robust inter-well correlation. They are primarily developed between stratigraphic units and exert a significant flow retardation effect [23]. In contrast, interlayers predominantly occur within individual sand layers, typically with thicknesses of less than several meters, and are characterized by poor lateral continuity and limited spatial extent. Although interlayers lack the capacity for regional-scale fluid regulation, they can substantially alter local oil-water distribution and water-flood sweep paths. Based on core observations and permeability analysis, the barriers and interlayers within the Donghe Sandstone reservoir are categorized into three distinct lithotypes: argillaceous, calcareo-argillaceous, and calcareous.

3.2.1. Genesis of Barriers and Interlayers

Integrating the outcrop surveys from the Bachu Xiaohaizi area with the analysis of over 60 core wells in the Hadeson region, argillaceous and calcareous barriers and interlayers are identified as the critical factors inducing intense reservoir heterogeneity. Argillaceous interlayers occur as thin beds or ribbons, originating from fine-grained deposition in quiescent (still-water) environments; their extremely low permeability constitutes the primary seepage barriers [24]. Calcareous interlayers are controlled by dense calcium carbonate cementation, characterized by lithological compactness, high hardness, and distinct low-

permeability features. Calcareo-argillaceous interlayers represent a transitional facies, where physical properties are jointly regulated by the proportions of argillaceous and calcareous components, resulting in differentiated permeability characteristics [25]. Existing data indicate that typical barriers exhibit permeabilities below 3 mD [26,27], whereas localized thin calcareo-argillaceous interlayers can reach up to 38.38 mD. Permeability is the deterministic metric for defining the flow-barrier attributes of these layers. When the permeability of weakly cemented interlayers exceeds 3 mD, their physical behavior transitions from “absolute sealing” to “seepage retardation.” In shoreface reservoirs, the quantitative permeability variance among argillaceous, calcareo-argillaceous, and calcareous units dictates the occurrence modes of remaining oil during high water-cut stages, alternating between “large-scale continuous enrichment” and “lens-like localized enrichment” [28]. Driven by frequent eustatic sea-level fluctuations, the intense hydrodynamic oscillations in the nearshore zone promoted the intermittent settling of fine-grained materials (clay and lime mud). The barriers and interlayers in the CIII-3S-7S sub-members are primarily concentrated in the nearshore zone, exhibiting a significant “intra-bar concentration” pattern in plan view. Furthermore, controlled by a slow progradational sea-level fall, interlayers are densely developed within the CIII-4S-6S sub-members, with argillaceous units specifically observed at the bar margins (Figure 4).



Figure 4. Core Log of Well HD4-44-2J in the Donghe Sandstone Formation.

The three types of interlayers identified within the study area exhibit comparable proportions within the overall stratigraphic framework. Statistical results (Figure 5) indicate that the thickness distributions of various barriers and interlayers are highly consistent, primarily ranging from 0.15 to 2.0 m, with a mean of approximately 0.6 m. Notably, the geometric dimensions of interlayers within a single architectural element demonstrate significant homogeneity; lengths are typically distributed between 350 and 475 m, with corresponding localized thicknesses concentrated between 0.3 and 0.4 m. These parameters suggest that barriers and interlayers of different genetic types exhibit similar sedimentary response characteristics in terms of their spatial distribution scales.

By integrating the discrimination logic of littoral interlayers/barriers with quantitative coupling formulas, the commonly used criteria for identifying interlayer/barrier types based on GR (Gamma Ray), SH (Shale Thickness), and shale content (Vsh) are established as follows:

$$Vsh = \frac{GR - GR_{min}}{GR_{max} - GR_{min}} \quad (1)$$

$$Vsh = \frac{2^{3.7 \times SH} - 1}{2^{3.7} - 1} = \frac{2^{0.037 \times (GR - 22)} - 1}{127.4} \quad (2)$$

When the shale content (Vsh) is greater than 0.4, it is identified as a muddy interlayer; when the shale content (Vsh) is between 0.2 and 0.4, it is identified as a calcareous-muddy interlayer; when the shale content (Vsh) is less than 0.2, it is identified as a calcareous interlayer.

However, relying solely on shale volume (Vsh) to differentiate types of barriers and interlayers introduces significant bias. In regions characterized by frequent tectonic activity and the coexistence of multi-genetic interlayers, the correlation between shale volume and interlayer lithotype is extremely weak. Consequently, utilizing a single indicator frequently leads to extensive misidentification of calcareous and calcareo-argillaceous units. Furthermore, constrained by discrepancies in logging tool models, inconsistent precision standards, and variations in operational protocols, traditional qualitative identification methods exhibit substantial limitations, with recognition accuracy hovering between 30% and 50%. This uncertainty severely restricts the high-fidelity characterization of complex heterogeneous reservoirs.

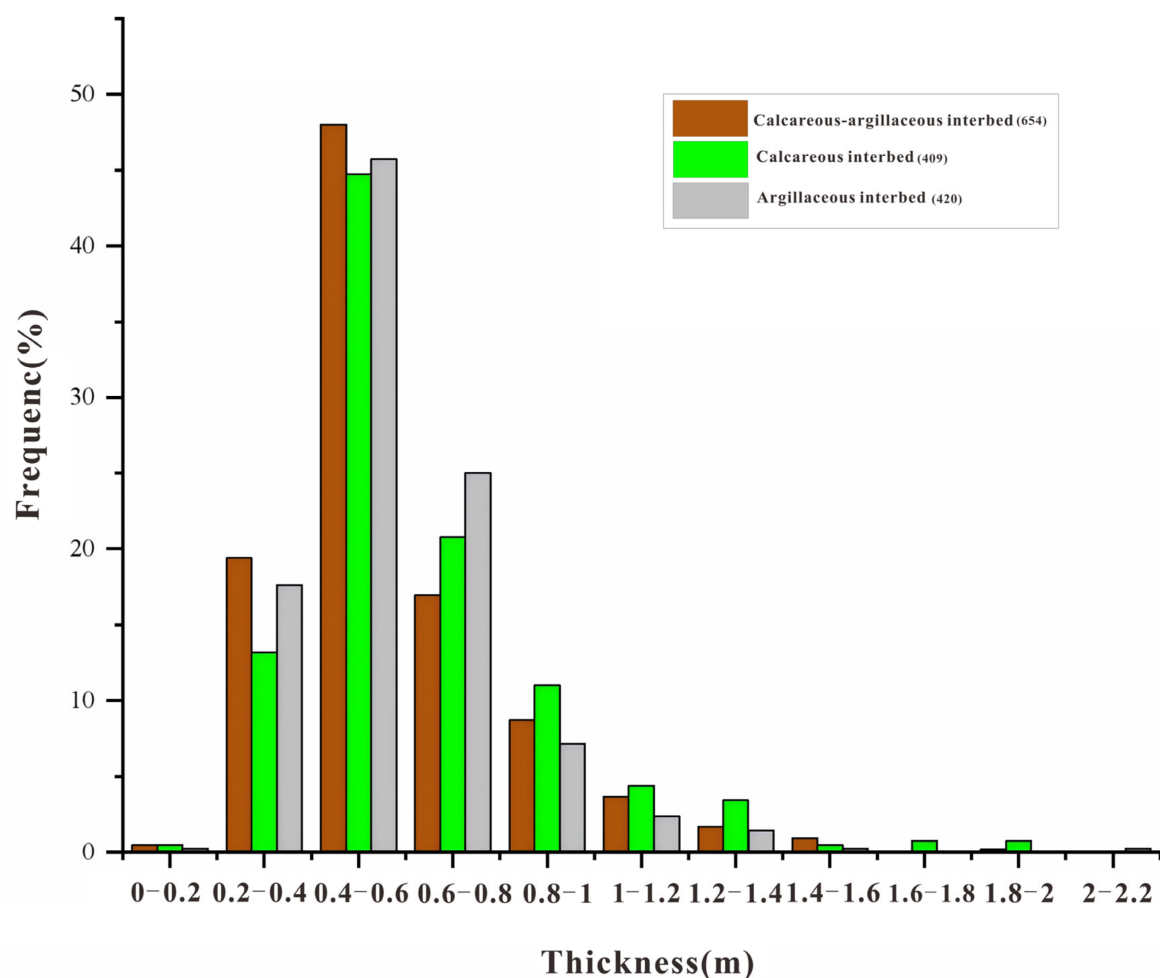


Figure 5. Thickness Distribution of Different Types of Sandwich Layers.

3.2.2. Analysis Based on 3D Cross-Plot Methodology

Following the methodology of previous studies [29,30], systematic analysis of the lithological response characteristics across various cross-plots reveals that the GR-DEN, GR-AC, and GR-CNL cross-plots exhibit the most significant litho-electric response disparities. GR serves as a proxy for shale content, while DEN indicates rock compactness. The relationship between GR and DEN follows a piecewise nonlinear negative correlation. For calcareous interlayers/barriers, the regression equation is $DEN = -0.003 \times GR + 2.65$; as GR increases due to minor shale admixture, bulk density decreases with a reduced absolute

slope. For calcareous-argillaceous interlayers/barriers, $DEN = -0.008 \times GR + 2.90$, indicating that as GR increases, shale content rises significantly, leading to a more pronounced density decrease. For argillaceous interlayers/barriers, the GR-DEN correlation is weak, making discrimination difficult. AC reflects rock porosity and lithologic compactness; specifically, increasing shale content enhances rock friability and increases sonic transit time. For calcareous interlayers/barriers, GR versus AC exhibits a piecewise nonlinear positive correlation, expressed as $AC = 0.35 \times GR + 45$. Minor shale influx elevates GR, marginally increases porosity, and slightly reduces sonic velocity, yielding a modest AC increase. For calcareous-argillaceous interlayers/barriers, the correlation is strong; substantial shale enrichment increases the clay mineral proportion, enhances rock friability, and significantly reduces sonic velocity, leading to a rapid AC increase. For argillaceous interlayers/barriers, the GR-AC correlation weakens, complicating identification. CNL reflects the abundance of hydrogen-bearing materials within the rock. Scatter distribution in the GR-CNL cross-plot indicates a piecewise nonlinear positive correlation. For reservoir sandstones and calcareous-argillaceous interlayers/barriers, $CNL = 0.002 \times GR + 0.05$, where minor shale admixture increases GR, and a slight increase in hydrogen-bearing clay minerals yields a modest rise in neutron porosity, demonstrating weak correlation. For calcareous-argillaceous interlayers/barriers, $CNL = 0.004 \times GR - 0.07$; a pronounced increase in shale content elevates the proportion of hydrogen-bearing clay minerals, and neutron porosity increases rapidly with shale content, exhibiting strong correlation. For argillaceous interlayers/barriers, the GR-CNL correlation remains weak, hindering discrimination. In summary, argillaceous interlayers/barriers lack a unified linear relationship across all three log attributes, rendering their identification inherently challenging.

To address the challenges posed by the weak logging responses of thin barriers and interlayers and the limitations of traditional single-curve identification, this study established a 3D logging cross-plot methodology integrating Gamma Ray (GR)–Density (DEN)–Compensated Neutron (CNL) and Gamma Ray (GR)–Density (DEN)–Acoustic Transit Time (AC) (Figure 6a,b). Initially, based on 654 measured core thin sections and petrophysical data points from over 60 cored wells in the study area, the precise lithologies identified via core observation were rigorously depth-matched and environmentally corrected with their corresponding borehole logging data. Representative data points from the GR, DEN, AC, and CNL curves were projected into the GR-DEN-CNL and GR-DEN-AC 3D coordinate systems, where identification intervals for different types of barriers and interlayers were delineated based on sample clustering characteristics. In practical application, argillaceous, calcareo-argillaceous, and calcareous interlayers can be effectively differentiated within these cross-plots. Taking the GR-DEN-AC model as an example, the 3D boundary criteria for the various interlayers were defined using a 95% confidence interval: argillaceous interlayers are statistically clustered in a domain characterized by “high GR (>39 API), high DEN (>2.6 g/cm³), and high AC (>58 μs/ft)”; calcareous interlayers strictly correspond to a cluster defined by “low GR (<49 API), low DEN (<2.49 g/cm³), and low AC (<53 μs/ft)”; and calcareo-argillaceous interlayers are situated within the overlapping transitional zone between these two end-members.

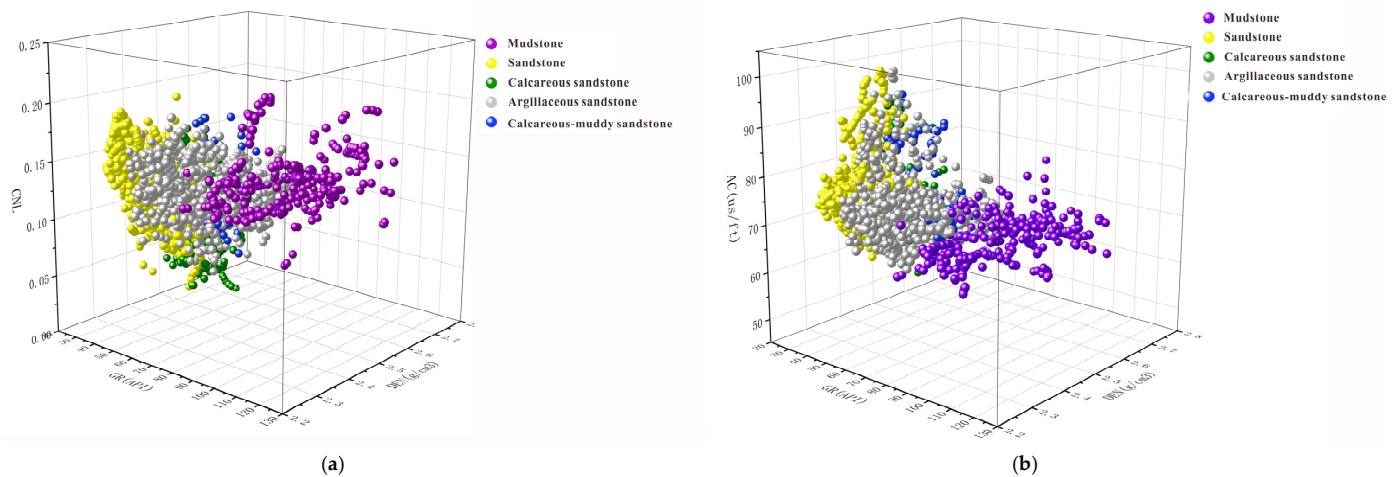


Figure 6. Interlayer Response Identification Range Table. (a) GR-DEN-CNL 3D Intersection Diagram; (b) GR-DEN-AC 3D Intersection Diagram.

3.2.3. Distribution and Patterns of Interlayer Spaces

During the vertical stacking of multi-stage shoreface sandbars, argillaceous barriers and interlayers, or distinct interfaces of abrupt physical property change, frequently develop between architectural elements; their developmental characteristics are governed by the architectural patterns of intra-bar accretionary bodies [31]. Drawing upon global studies of shoreface sandbar development and distribution [32,33], while integrating macroscopic core observations and single-well logging response analyses from the study area, it is established that the spatial distribution of these barriers and interlayers is primarily controlled by the distribution of beach-bar sand bodies [34,35]. These features are classified into inter-sandbody and intra-sandbody categories: inter-sandbody units are relatively thicker and predominantly function as barriers, whereas intra-sandbody units are thinner with more limited lateral extents and are primarily characterized as interlayers.

Interlayer Between Single Sand Bodies

Taking the HD4-44H well group as an example, the reservoir primarily comprises three individual sandbodies CIII-3J, CIII-4J, and CIII-5J characterized by Gamma Ray (GR) values of 22–51 API and Compensated Neutron (CNL) values of 0.01–0.2 (Figure 7a). This configuration partitions the reservoir into four sandbody stages, effectively separated by intervening barriers to form an alternating vertical sequence of “sandbody–barrier.” These inter-sandbody barriers range in thickness from 0.4 m to 2.2 m, with a mean of 1.5 m, and exhibit extremely low permeability and robust sealing capacity. Locally, these barriers demonstrate high lateral continuity; their dense lithological composition and low-permeability attributes constitute effective seepage barriers, which significantly baffle local fluid migration pathways and restrict cross-layer flow [36].

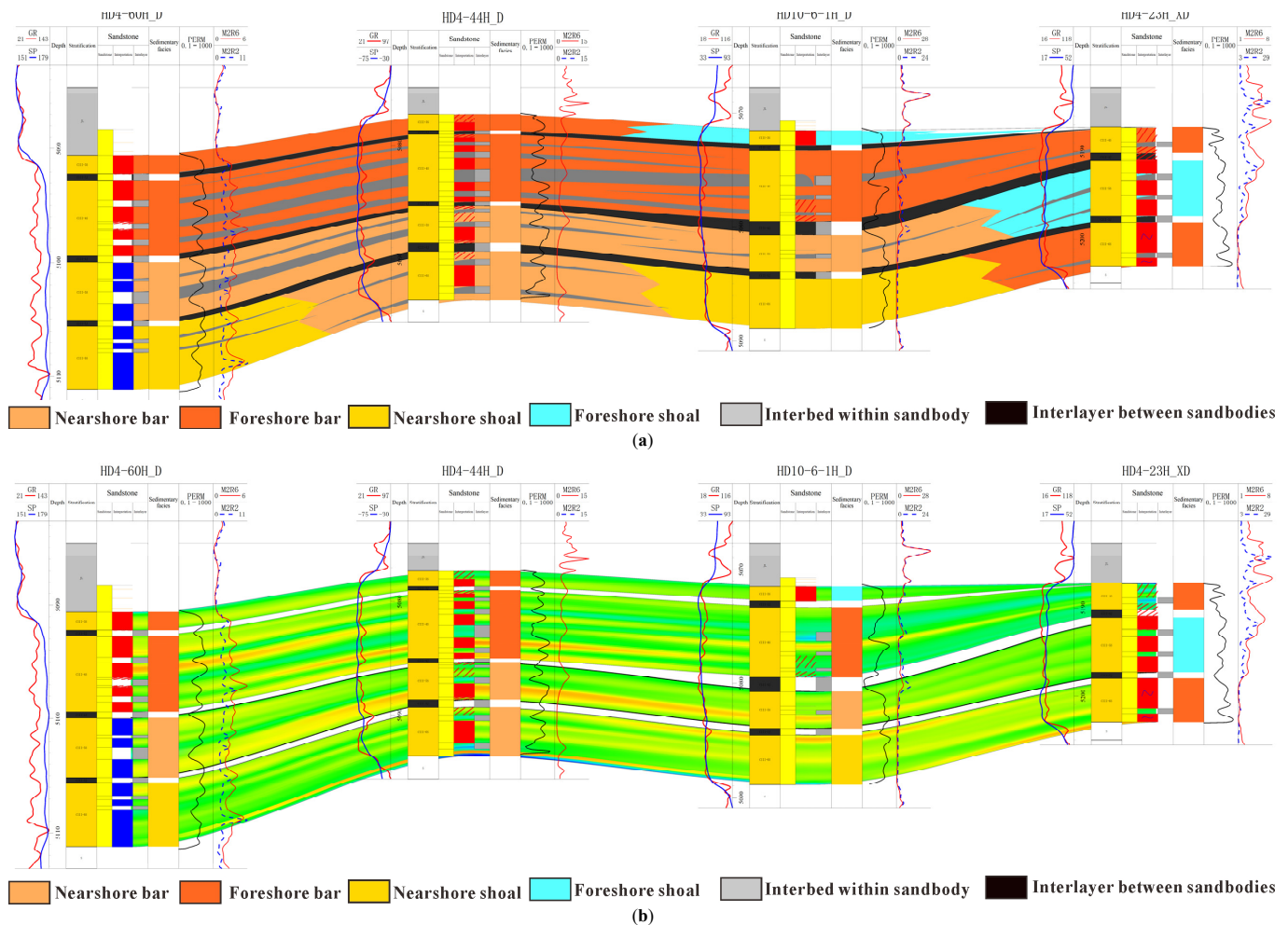


Figure 7. Combined Well Profile and Permeability Map for the HD4-44H Well Group. (a) Sedimentary Facies Profile from HD4-60H_D to HD4-23H_XD; (b) Permeability Profile from HD4-60H_D to HD4-23H_XD.

Interlayer Within Single Sand Body

Intra-sandbody interlayers are predominantly argillaceous and calcareo-argillaceous, characterized by low occurrence density and poor lateral continuity. Statistical analysis indicates a mean thickness of approximately 0.4 m and a mean length of 420 m (Figure 7b). Interlayers in the central zone of the sandbody are relatively stable, whereas those at the margins or within facies transition zones exhibit rapid pinch-out due to subsequent scouring or facies changes. The thickness-permeability contrast of these interlayers significantly reshapes the seepage field: thin, high-permeability interlayers at the base of CIII-5S facilitate the formation of preferential flow pathways; conversely, while the interlayers in the middle of CIII-4S exhibit increased thickness, they only provide moderate connectivity due to their relatively high permeability. These interlayers are mostly distributed in narrow strips (ribbon-like geometries). Owing to their limited baffling capacity, they fail to achieve complete fluid isolation and exert only a weak constraint on localized migration paths [37].

3.3. Control of Residual Oil in the Interlayer

Following long-term waterflood development, the spatial distribution patterns of remaining oil and the regularities of oil-water migration in the shoreface bottom-water reservoirs of the Hudson Oilfield have become increasingly complex [38]. Production performance data indicate that the study area has entered a high water-cut stage, with the comprehensive water cut exceeding 80%, while the recovery degree remains at only 25–30%.

Macroscopically, the remaining oil is characterized by “overall dispersion”; however, at the micro-scale, it exhibits intense “localized enrichment.” The hierarchy, thickness, and petrophysical variances of barriers and interlayers are the primary factors determining their sealing effectiveness, directly leading to differentiated water-flooding modes and remaining oil distribution patterns [39].

The Effect of the Interlayer on Residual Oil

The reservoirs in the study area possess strong natural energy; however, the shielding effect of barriers and interlayers significantly inhibits the vertical channeling of bottom water, resulting in a “semi-shielded” state [40,41]. Production performance data indicate that these reservoirs are characterized by prolonged water-free and low-water-cut production periods with slow water-cut increments; on well-test curves, the pressure derivative curves do not exhibit a significant decline. Influenced by this heterogeneity, the advancement velocity of injected water varies significantly in plan view: well HD4-63 in the south responded rapidly to injection, whereas well HD4-43 in the north exhibited a negligible response. This semi-shielded characteristic prevents direct vertical coning of bottom water, forcing it to bypass toward the amalgamation (incision-and-stacking) zones of sandbodies, thereby transforming into a slow lateral intrusion similar to edge water. This bypass flow pattern induces prominent “water-drive dead zones” within the injection-production system; the updip portions of barriers and interlayers are affected by the shielding, resulting in limited sweep efficiency and the formation of remaining oil enrichment zones. Conversely, connectivity pathways at sandbody amalgamation sites are prone to water channeling, causing sharp increases in water cut. Overall, the physical barrier effect reshapes the reservoir dynamic environment, forcing bottom water to transition from large-scale vertical coning to localized lateral bypass flow, with migration behavior manifesting as slow edge-water intrusion controlled by connectivity points. To quantitatively characterize the control mechanism of these layers on remaining oil, this study integrated production performance with well-logging water-out interpretation data for verification. Taking the HD4 well block as an example, a comparison between liquid production profiles and water saturation curves reveals that beneath argillaceous and calcareous barriers (>0.5 m thick), prolonged scouring by bottom and injected water has facilitated the development of high-permeability preferential pathways (pore-throat radii > 5 μm), where water saturation reaches 80–85%, and the water cut is nearly 95%. In contrast, the water-flooding degree is lower above the barriers and within lateral shielded zones (pore-throat radii < 2 μm), where water saturation remains at 40–50%, contributing to over 70% of the total oil production of the well.

The coupling relationship between perforation configurations and barrier/interlayer attributes is the core mechanism for analyzing reservoir heterogeneity and remaining oil distribution [42]. Taking the HD4-44H_D well group as an example, research indicates that the CIII4S barrier (thickness: 1.2 m; mean permeability: 0.35 mD) significantly obstructs the vertical connectivity of the CIII4S sub-member. In contrast, the intra-layer calcareo-argillaceous interlayers, characterized by limited thickness and poor stability, possess only restricted baffling capacity, leading to the formation of high-permeability preferential pathways at the base of CIII5S. By analyzing the perforation correspondence and dynamic characteristics of the injection-production well group, the sealing effectiveness of the barriers and interlayers can be quantitatively identified. The horizontal section of this well group penetrates the CIII3S-4S formations, with a gas-drive control degree of 75%. The effective pay zone thickness is 157.5 m (across 5 layers), and the marginal pay zone thickness is 62.5 m (across 2 layers); the perforated intervals are 5162–5253 m and 5253–5521 m. Regarding perforation correspondence, well HD4-44H penetrates the CIII3S, CIII4S, and CIII5S layers, showing a high degree of matching with the perforated intervals

of adjacent wells. Integrated analysis of development dynamic characteristics reveals that the CIII-5J interlayer between wells HD4-44H and HD4-43 has a thickness of 0.61 m and a permeability of 20.52 mD; the relative thinness and high permeability prevent effective hydrocarbon shielding, resulting in relatively dispersed remaining oil primarily concentrated in localized low-permeability areas with low displacement efficiency. Conversely, the CIII-5J barrier/interlayer between wells HD4-44H and HD4-44-2J has a thickness of 0.79 m and a permeability of 0.302 mD; despite being thin, its low permeability leads to poor connectivity, preventing crude oil from being effectively displaced. Consequently, it is difficult to mobilize the CIII-6S layer of well HD4-44-2J during water injection.

4. Results and Discussion

4.1. Fine Identification of Interlayers Using 3D Cross-Plot Method

Regarding the boundary delineation criteria in the 3D cross-plot methodology, traditional empirical manual line-drawing was abandoned. Instead, the Support Vector Machine (SVM) algorithm was introduced to perform nonlinear clustering analysis on multidimensional logging data, providing a rigorous mathematical basis for the boundary division among various barriers and interlayers from a statistical perspective. A more detailed classification is outlined as follows: for sandstone reservoirs, GR is 22–51 API, CNL is 0.01–0.2, DEN is 2.27–2.53 g/cm³, and AC is 55–100 µs/ft. The GR of argillaceous barriers and interlayers is generally high, with mudstone GR reaching 67–122 API and argillaceous sandstone GR ranging; their respective DEN values are 2.23–2.72 g/cm³ and 2.2–2.6 g/cm³, while AC is concentrated within the 58–99 µs/ft interval. The GR of calcareous barriers and interlayers is comparable to that of sandstone reservoirs (22–49 API), but their DEN is higher (2.49–2.67 g/cm³). For calcareo-argillaceous barriers and interlayers (calcareo-argillaceous sandstone), GR is 28–64 API, DEN ranges from 2.4 to 2.57 g/cm³, and AC is 58–94 µs/ft. The boundaries defined in this study were not empirically assigned but established based on the clustering distribution of cored well samples in 3D space, an approach similarly adopted by previous scholars [43] (Table 1). For samples within overlapping zones, manual corrections were executed by integrating core observations with adjacent well correlations. The primary advantage of this method is its capacity to simultaneously reflect argillaceous content, pore structure, and the degree of cementation and densification, thereby overcoming the low identification accuracy associated with using a single Vsh indicator in regions where multi-genetic barriers and interlayers coexist.

Statistical analysis of 15 typical development wells in the study area indicates that the misidentification rate of argillaceous barriers and interlayers using a single evaluation indicator reaches 38%, while the missed identification rate (omission rate) for “low-shale, strongly cemented” petrophysical barriers and interlayers is as high as 51%. The root cause of this discrepancy lies in the inability of a single indicator to effectively decouple the interference of cementation from shale volume Vsh estimations. By introducing the GR-DEN-AC 3D cross-plot, this study achieved precise identification across the dual dimensions of “lithology and petrophysics.” Taking well HD3-10 as a case study, calcareous interlayers were accurately identified utilizing their high DEN and low AC characteristics, successfully correcting previous omissions. Re-evaluation results demonstrate that the misidentification rate for argillaceous units decreased to below 6%, and the missed identification rate for petrophysical units was reduced to approximately 9%. This methodology effectively mitigates the interferences caused by heterogeneous mineral distribution and differential cementation, enhancing the overall identification accuracy by 32–42% and satisfying the requirements for the fine-scale development of shoreface reservoirs (Figure 8).

Single Well Sedimentary Facies Column of Well HD1-10

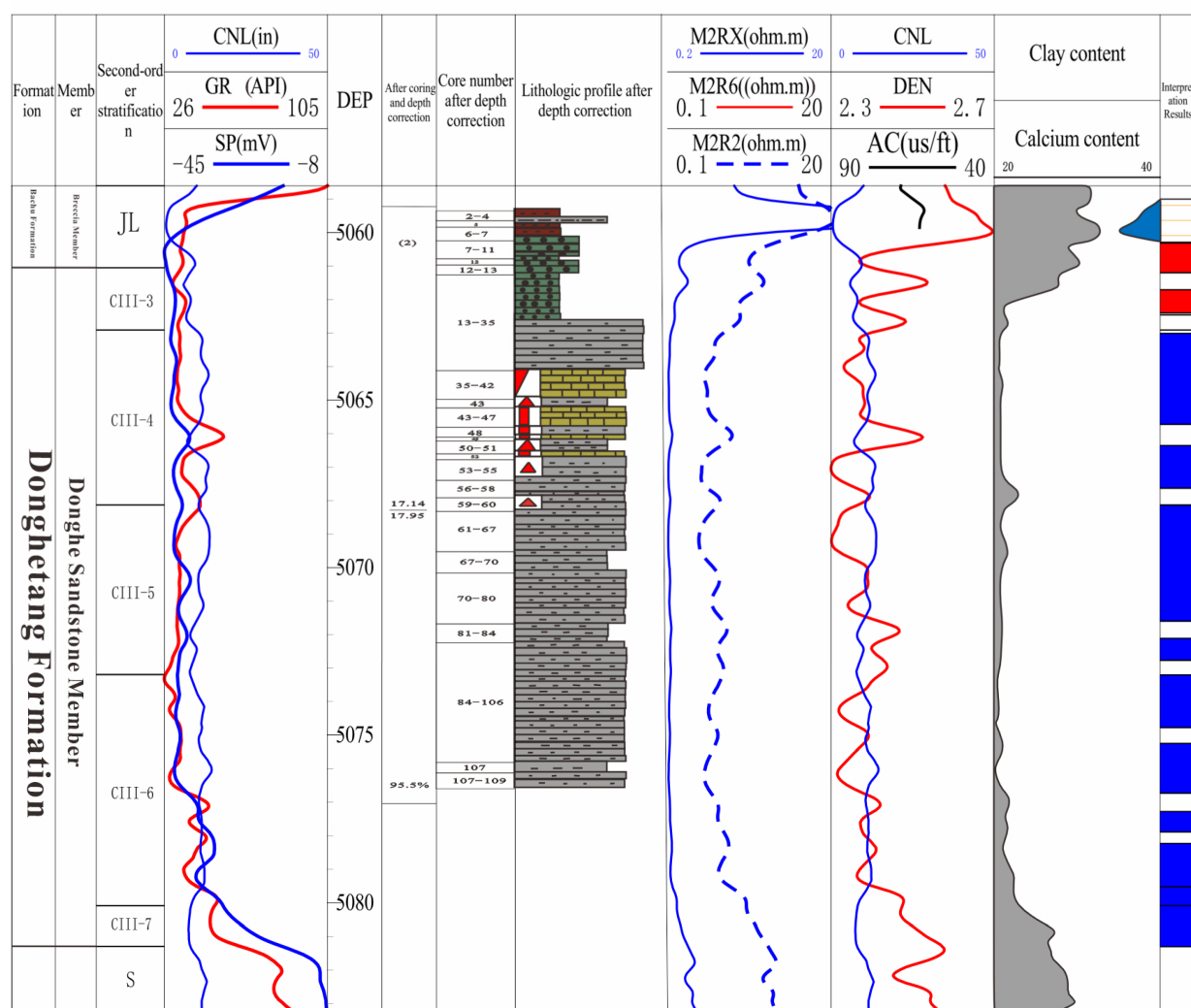


Figure 8. Single Well Sedimentary Facies Column of Well HD1-10.

Table 1. Interlayer Response Identification Range Table.

Lithology	Interbed	GR (API)	CNL	DEN (g/cm ³)	AC (μs/ft)
Sandstone	Reservoir	22–51	0.01–0.2	2.27–2.53	55–100
Mudstone	Argillaceous interbed	67–122	0.05–0.2	2.23–2.72	58–79
Argillaceous sandstone	Argillaceous interbed	39–77	0.04–0.2	2.2–2.6	58–99
Calcareous sandstone	Calcareous interbed	22–49	0–0.16	2.49–2.67	53–91
Calcareous-argillaceous sandstone	Calcareous-argillaceous interbed	28–64	0.05–0.17	2.4–2.57	58–94

4.2. Prediction of Residual Oil Distribution Under Interlayer Influence

By reviewing the injection interval data, dynamic injection pressure curves, and the correspondence of perforated intervals for the injection wells in this block, it was found that the spatial distribution and thickness of the barriers and interlayers directly govern the effective displacement range of the injection wells. Specifically, when the perforated intervals of the injection wells do not overlap with the horizons where barriers and interlayers are developed, the injected water can advance uniformly along high-permeability channels.

Conversely, when the perforated intervals span a thick barrier or interlayer, the injection pressure must overcome the flow resistance of these layers, restricting the vertical migration of the displacing fluid and resulting in effective displacement only within the target layer beneath the barrier/interlayer. The dual effects of the barriers and interlayers in this block are particularly prominent in the injection-production correspondence. First, in regions where the barriers and interlayers are relatively thick (>2 m) and vertically adjacent to the perforated intervals of the injectors, they exert significant shielding and sealing functions. This effectively prevents the upward channeling of injected water, delays the water breakthrough time of corresponding production wells, decelerates the water-cut rise rate, and consequently enhances the crude oil recovery factor. Second, when the barrier or interlayer is relatively thin and directly penetrated by the perforated intervals, its baffling effect is substantially weakened. The injected water is highly susceptible to forming channeling pathways along the contact interfaces between these layers and the sandbodies, triggering a high incidence of bottom-water channeling and causing some production wells to be shut in due to premature water flooding (water-out). Furthermore, the intrinsic attributes of barriers and interlayers—poor oil-bearing properties and strong sealing capacities—prevent the displacing fluid from effectively sweeping the crude oil within the shielded regions. This ultimately promotes the formation of localized remaining oil enrichment zones within the reservoir. Such enrichment zones are predominantly concentrated in the shielded areas above the perforated intervals of the injection wells, providing explicit targets for late-stage re-perforation and potential tapping.

Within the HD4-44H well area, the reservoir sand bodies of sublayers CIII-4S–CIII-5S in wells HD4-44H, HD4-44-2J, and HD4-43 are characterized predominantly by a “multi-sandbody cut-and-stack” pattern, with generally good lateral connectivity. However, laterally from well HD4-44H, stably distributed argillaceous and calcareous-argillaceous interlayers/barriers are developed, with a vertical thickness of 2–3 m, a lateral extent exceeding 800 m, and permeability below 3 mD, forming an effective baffle to injected water. Due to the blocking effect of these interlayers/barriers, the displacement fluid from injection wells can hardly advance effectively into the sublayer CIII-4S of well HD4-44H, resulting in insufficient depletion of this sublayer and making it a core area of remaining oil enrichment. As the main injection wells in the study area, wells HD4-43 and HD4-63 have injection intervals covering sublayers CIII-3S–CIII-5S. However, affected by the calcareous interlayers/barriers developed at the top of sublayer CIII-3S, the vertical percolation efficiency of the injected water is significantly constrained. This results in insufficient depletion of sublayer CIII-3S, with remaining oil exhibiting large-area, continuous enrichment in the structurally high parts of the well area (Figure 9a–g).

By integrating spatial morphological analysis of interlayers and intercalations with production performance monitoring of well patterns, quantitative identification of remaining oil enrichment zones has been achieved. The study reveals that well groups effectively shielded by interlayers and intercalations exhibit pronounced flow heterogeneity: adjacent stratigraphic intervals display markedly disparate water-cut escalation rates, localized horizons experience relatively low degrees of waterflooding, and correspondingly elevated remaining oil saturations are observed. To further substantiate this regularity, this study quantitatively examines the coupling relationship between dynamic production data and the developmental characteristics of interlayers and intercalations within typical well groups in the study area (Table 2).

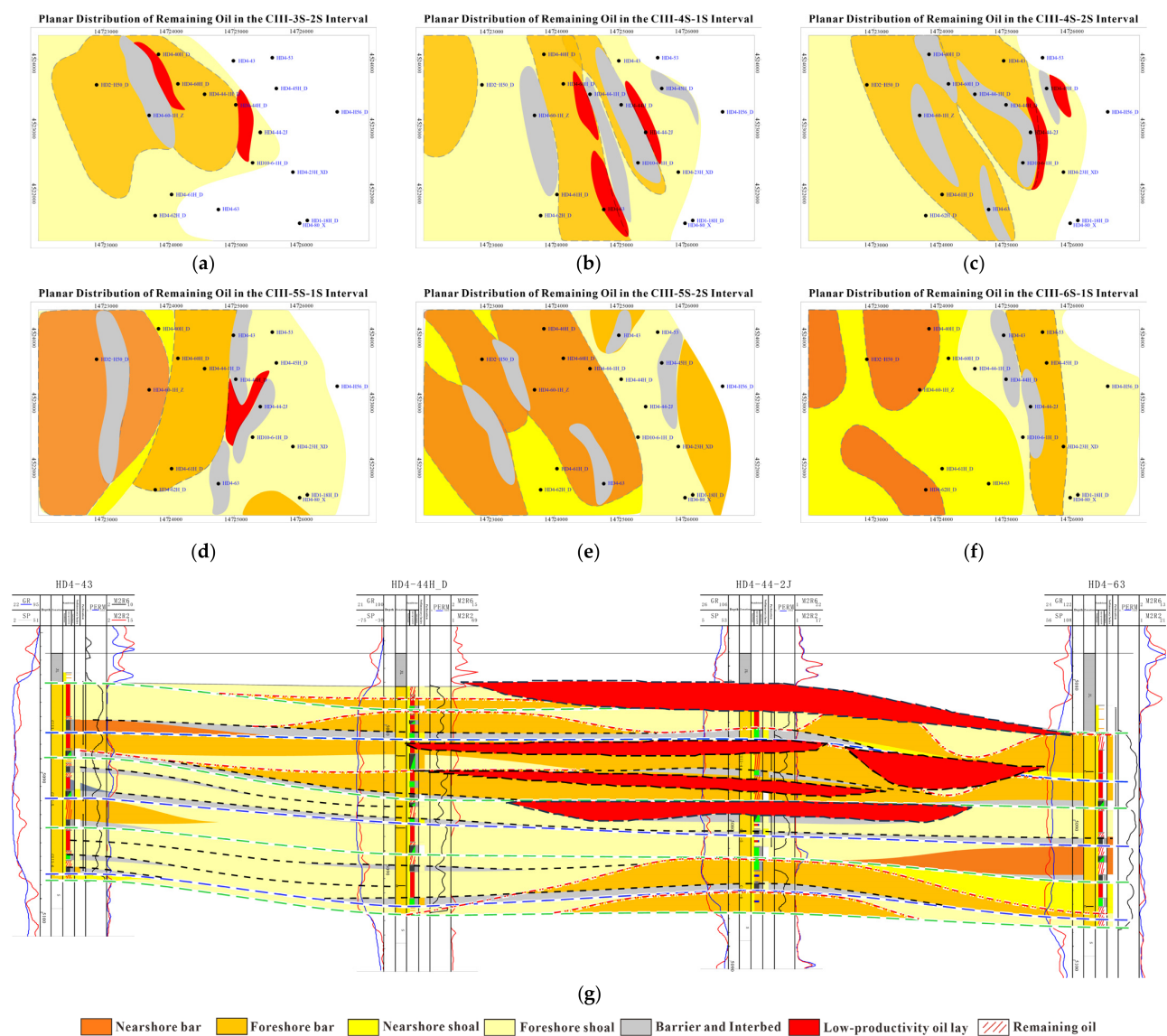


Figure 9. Plan and Section Views of Residual Oil Distribution in the HD4-44H Well Cluster. (a) Planar Distribution of Remaining Oil in the CIII-3S-2S Interval; (b) Planar Distribution of Remaining Oil in the CIII-4S-1S Interval; (c) Planar Distribution of Remaining Oil in the CIII-4S-2S Interval; (d) Planar Distribution of Remaining Oil in the CIII-5S-1S Interval; (e) Planar Distribution of Remaining Oil in the CIII-5S-2S Interval; (f) Planar Distribution of Remaining Oil in the CIII-6S-1S Interval; (g) Remaining Oil Distribution in the Sedimentary Facies Profile from HD4-43 to HD4-63.

Table 2. Production performance and interlayer/barrier development characteristics of representative well groups.

Well No.	Type of Barrier/Baffle	Thickness of Barrier/Baffle (m)	Water Breakthrough Time (Production Month)	Current Comprehensive Water Cut (%)	Cumulative Oil Production (10 ⁴ t)	Log Interpretation of Remaining Oil
HD4-44H	Calcareous barrier	1.2	34	76	12.5	The barrier constitutes an effective vertical seal. The interval above it remains unswept by injected water, exhibiting low water saturation (Sw < 50%) and representing a highly enriched remaining oil zone.

Table 2. Cont.

Well No.	Type of Barrier/Baffle	Thickness of Barrier/Baffle (m)	Water Breakthrough Time (Production Month)	Current Comprehensive Water Cut (%)	Cumulative Oil Production (10^4 t)	Log Interpretation of Remaining Oil
HD4-43	Argillaceous barrier	0.8	39	65	10.8	Lateral baffling is pronounced, creating a typical unswept area of waterflood. The lower part shows strong water flooding, whereas the middle to upper reservoir intervals display continuous enrichment of remaining oil.
HD10-6-1H	Calcareous-argillaceous baffle	0.6	15	85	8.2	The baffle merely induces local flow retardation, leading to fluid by-passing. Patchy remaining oil enrichment is present within the layer.
HD4-63	Weakly developed argillaceous baffle	0.2	5	96	4.1	The baffle is very thin and laterally discontinuous. Bottom water rapidly migrates upward by vertical coning, establishing a preferential water channel. The reservoir is generally strongly water-flooded with minimal remaining oil.
HD4-60H	Calcareous baffle	0.5	18	88	7.6	Due to permeability contrast, injected water advances preferentially along the lower part of the baffle. A remaining oil accumulation zone is formed at a subtle structural high above the baffle.

The type and thickness of interlayers and intercalations constitute critical factors governing the breakthrough timing of bottom/edge water and the evolutionary patterns of water-cut dynamics [44]. Production data demonstrate that Well HD4-44H, which penetrates a calcareous interlayer exceeding 1.0 m in thickness, exhibits a notably delayed water breakthrough at 34 months, with the current water-cut maintained at a relatively low level of 76%; the cumulative oil production from the interval above this interlayer has reached 12.5×10^4 t, rendering it an ideal target for sidetracking or reperforation-based potential tapping. In stark contrast, the HD4-63 well block, which lacks effective baffling, experiences extremely early water breakthrough (5 months), accompanied by a rapid escalation in water-cut exceeding 95%, thereby predisposing the interval to the formation of inefficient water circulation pathways. Such pronounced dynamic disparity substantiates the pivotal role of stable interlayers in suppressing bottom-water coning and preserving remaining oil accumulations.

4.3. Residual Oil Recovery Strategy Based on Interlayer Separation

Since entering the high-water-cut stage, oil production in the Hadexun Oilfield has declined annually due to the influence of interlayer/barrier distribution. The current recovery factor of the HD4-44H well group is 55.53%. The peak production of the well group was 360 t/d; currently, the daily liquid production is 623.5 t/d and the daily oil production is 44.17 t/d. After adjustment using a “perforation + screen completion” method, because the horizontal section of the production well is located above the interlayers/barriers, the remaining oil sheltered beneath the interlayers/barriers cannot be effectively mobilized. This restricted development sweep range directly results in low well productivity, with a liquid production decline rate of 10.7%. Based on the latest understanding of interlayer/barrier

distribution patterns and remaining oil distribution, the oilfield has optimized its remaining oil potential tapping strategy and implemented a second-round infill drilling program. Well HD4-63 in the southern part of the well group and well HD4-43 in the northern part were selected as water injection wells, and well HD4-44H, as the central well, was converted to gas injection, establishing a “dual injection-single production, top potential tapping” three-dimensional injection-production well pattern. The gas flooding is intended to activate the potential of remaining oil between wells, aiming to effectively mobilize the remaining oil in structurally high areas and zones sheltered by interlayers/barriers, thereby alleviating the production decline pressure of the well group and enhancing the overall development performance and recovery factor of the reservoir.

5. Conclusions

- (1) The genetic and petrophysical differences among the three types of interlayers/barriers in marine littoral reservoirs, as well as their control over the types of flow barriers, have been clarified. Based on core and petrophysical analyses, three types of interlayers/barriers—argillaceous, calcareous, and calcareous-argillaceous—are developed in the littoral facies reservoirs of the Donghe Sandstone in the Tarim Basin. These three types occur in comparable proportions, with average thicknesses ranging from 0.58 to 0.63 m. Among them, argillaceous interlayers/barriers exhibit the lowest permeability (<3 mD) and constitute effective flow barriers. Calcareous interlayers/barriers are characterized by low permeability due to tight cementation. Calcareous-argillaceous interlayers/barriers show permeability values reaching up to 38 mD, and serve as local flow pathways.
- (2) A dual control mechanism of interlayers/barriers on waterflood pathways and remaining oil accumulation has been revealed. Under semi-confined conditions, interlayers/barriers suppress vertical bottom-water coning, forcing injected water to flow laterally along sandbody cut-and-stack contacts. This results in the formation of unswept zones updip of the interlayers/barriers and sheltered areas above the perforated intervals of injection wells. Dynamic data indicate that water breakthrough time is positively correlated with interlayer/barrier thickness. In contrast, well zones lacking effective barriers exhibit extremely early water breakthrough, with water cut rapidly increasing and leading to the development of ineffective water circulation pathways.
- (3) This study confirms that interlayers/barriers in littoral reservoirs are the fundamental cause of the remaining oil distribution pattern characterized by “macroscopically dispersed yet microscopically locally enriched”. It is clarified that the remaining oil is predominantly continuously enriched in the sheltered zones above the perforated intervals of injection wells, as well as in microstructural highs. This finding not only directly addresses the research objective of elucidating remaining oil distribution patterns but also provides a clear geological targeting framework and scientific basis for fine-scale reservoir potential tapping in the Hadexun Oilfield and other analogous marine littoral reservoirs during the late high-water-cut stage.

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