

Article

Characterization of Laminae and Lamina-Associated Fractures in the Tight Oil Reservoir of Xifeng Oilfield, Ordos Basin: CT Scanning of Full-Diameter Cores from Horizontal Well X119-19-39H

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Abstract

This study focuses on the Chang 8 Member tight sandstone reservoir in the Xifeng Oilfield. Integrated approaches including 3D reconstruction of CT digital cores, seepage simulation, and multi-parameter coupling analysis were employed to systematically classify lamina types, quantitatively characterize lamina-associated fractures, and elucidate the pore–lamina fracture coupling seepage mechanisms. The results show that laminae in the study area can be categorized into three types: banded, inclined, and cross-laminated. Lamina-associated fractures are dominated by bedding-parallel fractures, with a small number of cross-bedding fractures having developed in cross-laminated intervals. The development of lamina-associated fractures is jointly controlled by sedimentary heterogeneity and mechanical differences between interlaminar layers. A significant positive correlation exists between the volume proportion of interlaminar layers and fracture porosity ($R^2 = 0.8913$). Cross-laminated intervals exhibit the optimal fracture parameters, with fracture porosity reaching up to 3.6% and maximum fracture volume exceeding 3500 mm³, facilitating the formation of three-dimensional interconnected fracture networks. Distinct pore–lamina fracture coupling patterns are observed in different lamina types: independent development with weak coupling in banded laminae, segmented synergy with heterogeneous coupling in inclined laminae, and strong synergy with network coupling in cross-laminated intervals. In cross-laminated sections, matrix porosity and fracture porosity evolve synchronously, yielding the highest permeability (up to 7.3 mD) and superior storage–permeability performance. Seepage simulations confirm that permeability in tight reservoirs is not directly controlled by matrix porosity; instead, lamina-associated fractures act as the dominant fluid migration pathways. Cross-laminated fractures form multi-directional high-efficiency seepage networks, while banded and inclined laminae exhibit unidirectional linear seepage and segmented dominant channeling characteristics, respectively. These findings provide critical geological insights for sweet spot evaluation, horizontal well trajectory optimization, and hydraulic fracturing design in tight oil reservoirs.



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Keywords: tight sandstone reservoir; Xifeng oilfield; CT scanning; lamina; lamina-associated fracture; pore–fracture coupling; storage and permeability control

1. Introduction

Against the backdrop of advancing exploration and development technologies and the gradual depletion of conventional oil reserves, tight sandstone oil reservoirs have emerged as one of the focal points in the field of unconventional hydrocarbon development [1]. The Ordos Basin, as a core area for tight oil exploration and development in China, hosts extensive tight sandstone reservoirs with abundant hydrocarbon resources and promising exploration prospects [2]. The southern margin of the Ordos Basin is characterized by well-developed Mesozoic faults and fractures with strong tectonic activity, where tight sandstone reservoirs with pervasive laminae are deposited. Multi-scale natural fractures play a pivotal role in the hydrocarbon accumulation and enrichment of tight oil reservoirs in southern Ordos [3]. The Chang 8 Member tight oil reservoir of the Triassic Yanchang Formation in the Xifeng Oilfield, located in southwestern Ordos, has become a typical block for large-scale and cost-effective tight oil development in the basin due to its substantial resource endowment and favorable development potential. However, the superimposed effects of sedimentary and diagenetic processes have resulted in strong reservoir heterogeneity, complex hydrocarbon seepage pathways, and generally low natural productivity, which severely restrict the efficient exploration and precise development of these tight oil reservoirs [4].

Extensive geological research and field development practices have confirmed that laminae [5,6], as the most fundamental and extensively developed microscale sedimentary structural units in fine-grained tight sandstones, exert a dominant control on reservoir heterogeneity through their morphology, assemblage, and spatial distribution. Lamina-associated fractures, which develop along lamina interfaces, represent critical storage spaces and seepage pathways in tight oil reservoirs. Their development degree, spatial distribution, and connectivity directly determine the formation and distribution of reservoir “sweet spots” and are the core geological factors influencing horizontal well productivity and hydraulic fracturing effectiveness.

Traditional techniques for characterizing laminae and fractures in tight reservoirs primarily include core visual observation, conventional thin section identification, scanning electron microscopy (SEM) analysis, and imaging logging. While these methods have advanced reservoir characterization to some extent, they suffer from significant limitations. Core observation and thin section analysis only provide information on laminae and fractures from core surfaces or two-dimensional cross-sections, failing to reveal their three-dimensional spatial distribution and lacking sufficient resolution for micron-scale laminae and microfractures. Other geophysical logging methods enable in situ detection but have limited resolution and produce interpretations with inherent ambiguity [7]. In recent years, high-resolution industrial CT scanning technology has emerged as a key technique for microstructural characterization of tight reservoirs due to its core advantages of non-destructive testing, high resolution, three-dimensional visualization, and accurate quantification. Based on X-ray penetration principles, this technology acquires two-dimensional tomographic images with micron-scale (50 μm) resolution without damaging core samples. Three-dimensional reconstruction techniques are then used to restore the true spatial morphology of laminae, pores, and fractures within the core, while simultaneously quantifying various morphological parameters of fractures [8,9].

Against this background, this study takes full-diameter cores from the Chang 8 Member of horizontal well X119-19-39H in the Xifeng Oilfield as the research object, and carries

out a fine-scale single-well dissection of lamina and lamina-associated fracture systems. High-resolution CT scanning technology is utilized to leverage the grayscale difference response of CT images to materials of different densities, enabling three-dimensional visualization reconstruction of lamina-associated fractures. Key parameters including fracture porosity, density, and volume are quantitatively extracted to reveal the three-dimensional distribution characteristics of lamina-associated fractures at the full-diameter core scale [10–12]. The CT characteristics and quantitative parameters of various lamina types are finely characterized, and the identification criteria, development patterns, and coupling relationships between laminae and lamina-associated fractures are clarified. Finally, the mechanisms by which laminae and lamina-associated fractures control reservoir storage and permeability are elucidated.

2. Geological Setting

The Ordos Basin, located at the junction of the eastern and western tectonic domains in China, is the second largest continental sedimentary basin in China with an area of approximately $3.7 \times 10^5 \text{ km}^2$. It is divided into six first-order tectonic units: the Western Thrust Belt, Tianhuan Depression, Yishan Slope, Jinxi Flexure Belt, Yimeng Uplift, and Weibei Uplift (Figure 1a) [13,14]. During the continuous evolution and stable subsidence of the basin, the Upper Triassic Yanchang Formation—a suite of terrigenous clastic rocks characterized by fluvial-lacustrine facies—was deposited. Based on the evolutionary characteristics of the lake basin, sedimentary cycles, and marker beds such as tuff or carbonaceous mudstone with distinct electrical signatures, the Yanchang Formation is subdivided into ten oil-bearing members from bottom to top (Chang 10 to Chang 1) (Figure 1b) [4]. During the Late Triassic, the Xifeng Oilfield was situated in the southwestern depositional system of the basin and experienced the entire evolutionary process of the lake basin from initiation, development, and peak to shrinkage and extinction, forming multiple sets of source–reservoir–cap assemblages. The Chang 8 Member is the main oil-bearing interval, dominated by fluvial and delta plain subfacies. Its lithology is primarily black and grayish-black fine-to medium-grained lithic arkose, with an average porosity of 8.4% and average permeability of 0.29 mD, classifying it as a low-porosity and ultra-low-permeability reservoir. Laminae and lamina-associated fractures are well developed, dominated by low-angle fractures. With abundant hydrocarbon resources, it has long been a primary exploration and development target in the Ordos Basin [4].

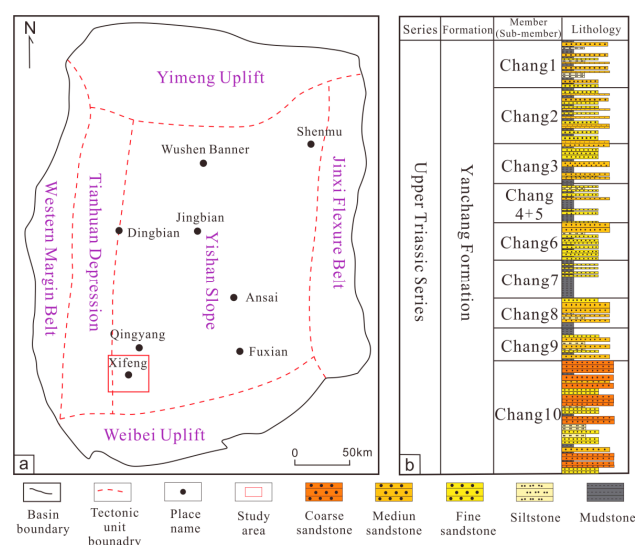


Figure 1. Tectonic division of the Ordos Basin (a) and comprehensive stratigraphic column of the Upper Triassic Yanchang Formation (b). Adapted from reference [4].

3. CT Scanning and Fracture Image Processing

Digital core technology is based on three-dimensional (3D) grayscale images acquired by scanning electron microscopy (SEM) or micro-nano CT. Relying on computer programming and reconstruction algorithms, it enables 3D visualization and reconstruction of microstructures such as pores, laminae, and fractures within cores (the second figure of this section) and completes quantitative parameter characterization. This technology restores the true internal structure of cores through algorithmic superposition of multi-resolution CT sequential images and 3D modeling. However, deviations such as noise and artifacts are easily introduced during photoelectric signal conversion, image segmentation, and reconstruction processes, which may cause local distortion of micron-scale lamina boundaries and microfracture morphology, thereby affecting the accuracy of subsequent quantitative parameter extraction [15,16]. Common filtering and denoising methods in image processing include mean filtering, median filtering, and watershed filtering [17]. In this study, the watershed denoising method implemented in the 3D image processing software Amira-Avizo 2025.1. was applied to denoise and smooth the acquired CT images. Subsequently, the full-diameter core was scanned via CT scanning to obtain the original CT slice images of the core (Figure 2a). In the original images, fractures show distinct grayscale anomalies due to density differences relative to the surrounding lithology. Subsequently, image processing techniques such as image binarization were applied to separate fracture regions from the background lithology, yielding binary images containing only fractures (Figure 2b). CT scanning was performed on full-diameter cores from the study well using a Geoscan-200 instrument at a scanning resolution of 50 μm . This approach accurately depicts the development characteristics and spatial distribution of lamina-associated fractures in the tight oil reservoir of well X119-19-39H and constructs a 3D geological model of these fractures. It provides an intuitive basis for quantitative extraction of key parameters including fracture density, volume, and number, and offers strong support for fine characterization of lamina-associated fractures and research on reservoir seepage mechanisms in tight oil reservoirs [18–20] (also see Figure 3).

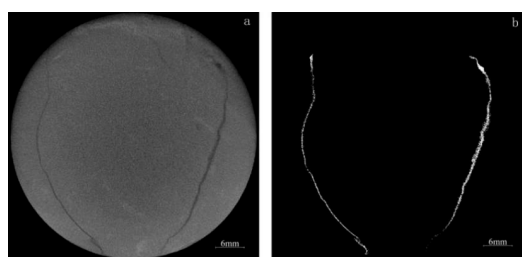


Figure 2. Fracture extraction process of CT slice images ((a) Original image; (b) Binarized image).

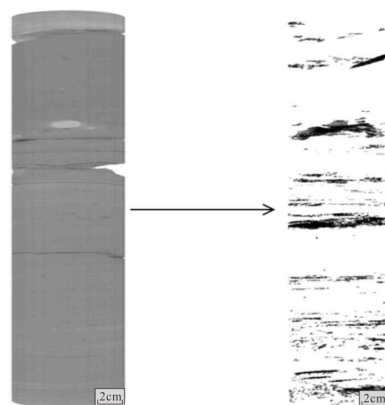


Figure 3. Schematic of 3D fracture reconstruction and visualization.

4. Three-Dimensional Characteristics of Laminae and Lamina-Associated Fractures

4.1. Classification of Laminae and Lamina-Associated Fractures

Laminae are the smallest-scale bedding units in fine-grained sedimentary rocks, formed by periodic variations in material composition, grain size, or sedimentary hydrodynamic conditions. They represent the core microstructures controlling reservoir heterogeneity and the development of lamina-associated fractures in the Chang 8 Member tight reservoir of the Xifeng Oilfield. Lamina-associated fractures are microfractures formed by rupture along mechanical weak zones such as lamina interfaces during multi-stage geological processes including sedimentation and diagenetic modification. Their development and distribution are controlled by material composition, mechanical contrasts, and late-stage tectonic activity [21–23]. Laminae of different morphologies in the Chang 8 Member reservoir not only record variations in hydrodynamic conditions and sediment supply during the depositional period but also directly influence the opening degree and distribution pattern of fractures during the diagenetic stage. Based on core profile observations from CT scanning, lamina morphologies in 113 m of samples from the study area were classified and statistically analyzed, and three main types were identified: banded laminae, inclined laminae, and cross-laminated laminae (Figure 4). Corresponding to these lamina morphologies, three types of lamina-associated fractures were distinguished. Inclined lamina-associated fractures account for the largest proportion, followed by cross-laminated fractures, while banded fractures are the least abundant, indicating abundant and well-developed natural fractures in the study area (Figure 5).

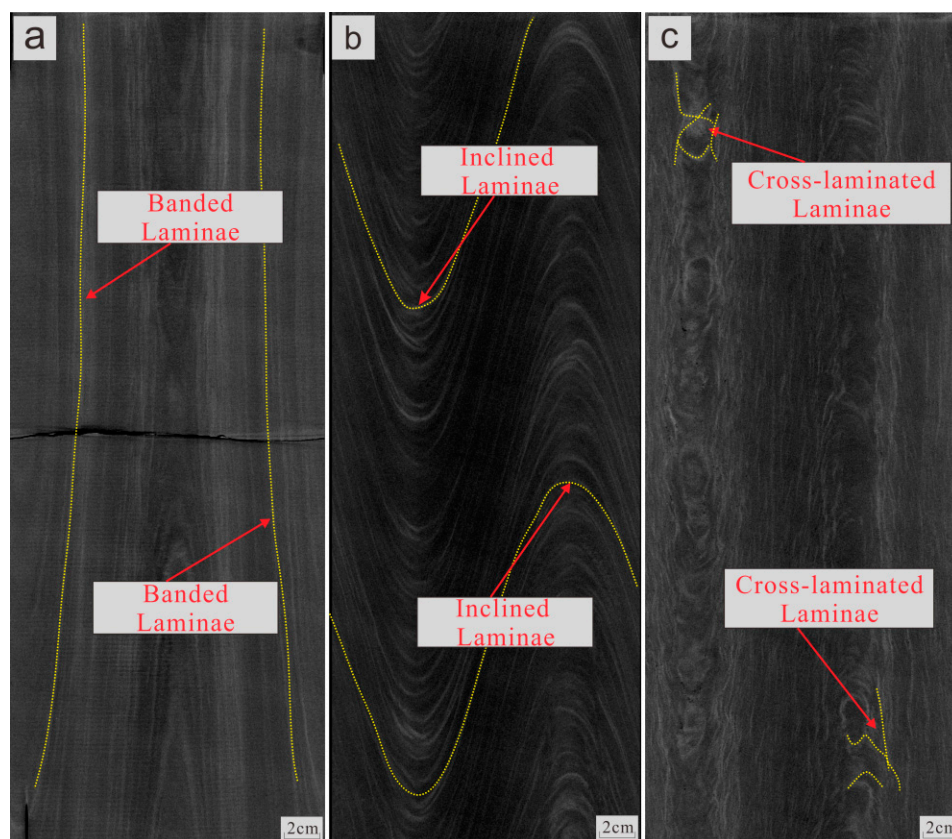


Figure 4. Classification of different lamina morphologies in CT core cross-sections ((a) Banded; (b) Inclined; (c) Cross-laminated).

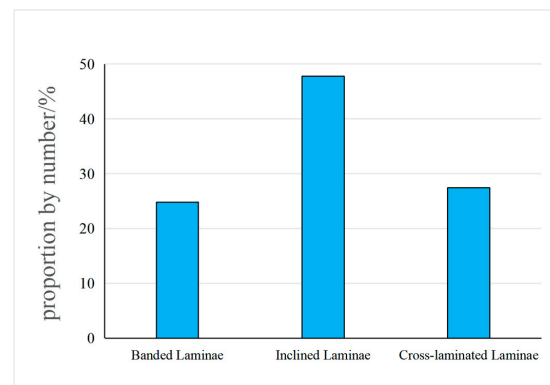


Figure 5. Fracture number proportion by lamina morphology.

4.2. Three-Dimensional Visualization and Quantitative Characterization of Lamina-Associated Fractures

As a typical unconventional reservoir, tight sandstone possesses a multi-level coupled pore–fracture (lamina-associated fracture) storage–seepage system at the microscale. This system constitutes the core space for hydrocarbon occurrence and the key pathway for fluid flow, playing a critical role in hydrocarbon accumulation, migration, and efficient development. According to their relationship with rock strata occurrence, fractures in the study area can be divided into bedding-parallel fractures and cross-bedding fractures. Bedding-parallel fractures develop along sandstone laminae or bedding planes, with their genesis primarily related to sedimentary laminae, lithological interfaces, and bedding weak zones. Their occurrence is nearly parallel to rock bedding or follows lamina development, exhibiting curved, discontinuous, and pinch-out morphological characteristics, and they show an almost paragenetic relationship with laminae. In contrast, cross-bedding fractures mostly obliquely or perpendicularly cut lamina planes and are primarily controlled by tectonic stress. Their development is further governed by the lithological association and mechanical bedding of sedimentary strata [24,25]. In the study area, banded and inclined laminae predominantly develop bedding-parallel fractures, with fracture porosities of 2.06% and 1.82%, respectively (Figure 6a,b). Cross-laminated intervals develop both bedding-parallel fractures and a small number of cross-bedding fractures, with the maximum fracture porosity reaching 3.57% (Figure 6c).

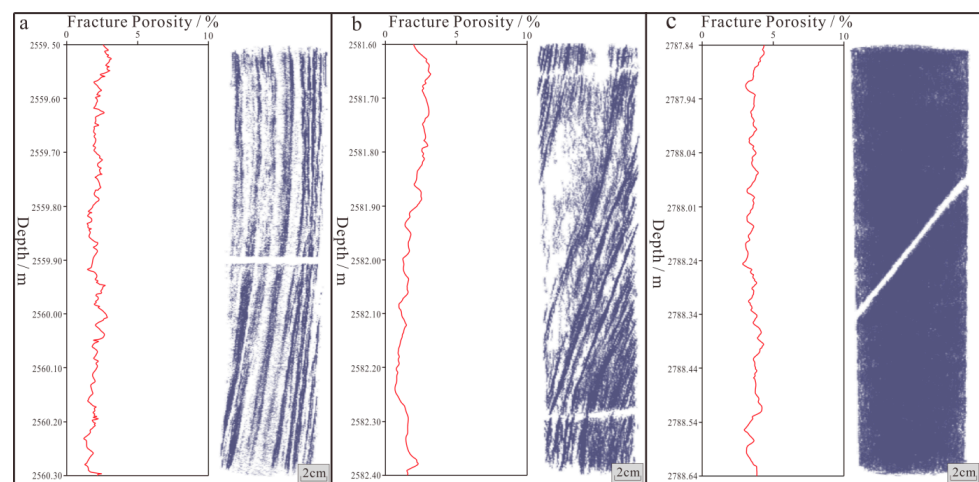


Figure 6. Fracture porosity of lamina-associated fractures and their 3D models in full-diameter cores ((a) Banded lamina-associated fractures and fracture porosity; (b) Inclined lamina-associated fractures and fracture porosity; (c) Cross-laminated lamina-associated fractures and fracture porosity).

4.3. Internal Structural Characteristics of Lamina-Associated Fractures by Morphology

Statistical analysis of lamina-associated fractures classified by morphology was conducted on 113 m of tight sandstone samples from horizontal well X119-19-39H, and the derived parameters are presented in Table 1. As shown in the table, significant differences exist in fracture volume, density, number, and fracture porosity among the three types of lamina-associated fractures. In terms of fracture volume, cross-laminated lamina-associated fractures have the highest average value of 1705.49 mm³, significantly exceeding those of the other two types. All three fracture types exhibit extremely high dispersion in volume, with maximum values of 3717.42 mm³, 4035.02 mm³, and 3397.65 mm³, and minimum values as low as 2.47 mm³, 8.32 mm³, and 18.55 mm³, respectively. The average fracture density of all three types ranges from 100 to 140 fractures per meter. Cross-laminated fractures have the highest average density (138.5 fractures/m), followed by banded fractures (125.5 fractures/m), while inclined fractures have the lowest average density (104 fractures/m). In terms of fracture number and porosity, inclined lamina-associated fractures are the most numerous, totaling 56,075 fractures, while the numbers of banded and cross-laminated fractures are relatively comparable. The average fracture porosity follows the order: cross-laminated (2.01%) > inclined (1.66%) > banded (1.55%). Overall, the parameters of lamina-associated fractures vary significantly with morphology: cross-laminated fractures are characterized by large single-fracture volume and high overall development degree; inclined fractures have the largest number and relatively high porosity; banded fractures exhibit stable overall development but the lowest fracture porosity. Additionally, the single-fracture volume distribution is highly heterogeneous for all three types.

Table 1. Lamina-associated fracture parameters by morphology in horizontal well X 119-19-39H.

Fracture Type	Fracture Volume/mm ³			Fracture Density (Fractures/m)			Fracture Number	Average Fracture Porosity (%)
	Maximum	Minimum	Average	Maximum	Minimum	Average		
Banded	3717.42	2.47	1265.24	180	62	125.5	42,168	1.55
Inclined	4035.02	8.32	1265.24	250	23	104	56,075	1.66
Cross-laminated	3397.65	18.55	1705.49	193	84	138.5	42,888	2.01

Statistical analysis of fracture volume distributions by interval reveals distinct differences in volume scales among the three types of lamina-associated fractures (Figure 7a). Banded lamina-associated fractures show a relatively uniform volume distribution: 25% fall in the 0–500 mm³ interval and 21.42% in the 500–1000 mm³ interval, with small-to-medium volume fractures dominating. Notably, the 1500–2000 mm³ and >2500 mm³ intervals each account for 17.5% of the total. Inclined lamina-associated fractures are dominated by relatively small volumes: the volume frequency is 29.62% in the 0–500 mm³ interval and 22.22% in the 500–1000 mm³ interval, and frequency decreases continuously with increasing fracture volume. Cross-laminated lamina-associated fractures exhibit a trend toward large volumes: the proportion in the small-volume intervals (0–500 mm³ and 500–1000 mm³) is 12.9%, lower than the other two types. Frequency increases progressively with increasing volume, reaching 19.35% in the 1000–1500 mm³ interval and peaking at 25.8% in the >2500 mm³ interval.

Banded laminae are flat and continuous with uniform petrophysical and mechanical properties within layers, resulting in balanced fracture scale development. Small-to-medium volume fractures are the most abundant, while a significant number of large-volume fractures are also preserved, with stable development across all size ranges. Inclined laminae have undulating interfaces and high lithological plasticity, such that microfractures only initiate readily at local weak planes and rarely propagate and connect. Consequently, the vast majority are small-volume microfractures, with overall small fracture scale and

high dispersion. Cross-laminated laminae contain numerous bifurcated and intersecting mechanical weak interfaces. Under diagenetic compaction and tectonic stress, fractures are more likely to interconnect, propagate, and coalesce, ultimately forming abundant large-volume, high-extent dominant fractures.

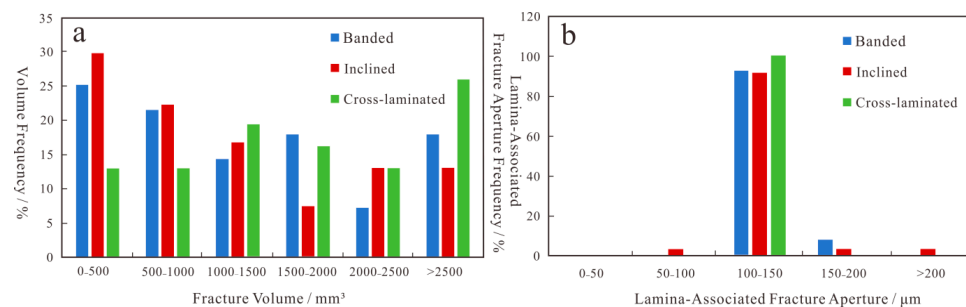


Figure 7. Volume and aperture frequency histograms of lamina-associated fractures by morphology in well X 119-19-39H. (a) Volume histogram of laminar fractures with different morphologies. (b) Aperture frequency histogram of laminar fractures with different morphologies.

Fracture aperture, a quantitative parameter describing fracture development characteristics, serves as the foundation for evaluating fracture effectiveness and provides critical guidance for the exploration and development of tight oil reservoirs [26,27]. Common methods for measuring fundamental fracture aperture parameters are generally categorized into two types: direct measurement using 3D visualization software, which offers high accuracy; and programming-based measurement, typically implemented in MATLAB R2026, which is convenient, efficient, and suitable for batch processing [28]. In this study, direct measurement and quantitative characterization of fracture aperture were performed using the 3D visualization software Avizo, and aperture frequency histograms for banded, inclined, and cross-laminated lamina-associated fractures were generated (Figure 7b).

In terms of distribution characteristics, the apertures of banded and cross-laminated lamina-associated fractures are concentrated in the 100–150 μm interval, accounting for 92.3% and 100% of the total, respectively. The apertures of inclined lamina-associated fractures are also predominantly concentrated in the 100–150 μm interval, accounting for 91.17%, with minor scattered distributions in the 50–100 μm, 150–200 μm, and >200 μm intervals. Banded lamina-associated fractures are flat and continuous with laterally stable lithological and mechanical properties, resulting in minimal variations in interlayer stress differences and negligible differences in fracture opening degree. Their apertures are narrowly concentrated in the 100–200 μm range, with an overall stable and controllable distribution. Cross-laminated lamina-associated fractures are formed by multiple sets of mutually cutting and intersecting laminae, leading to uniform internal stress release and consistent overall stress conditions on fractures. This ultimately results in a lamina-associated fracture system with highly uniform aperture and exceptional homogeneity. In contrast, inclined lamina-associated fractures have undulating interfaces and frequent rhythmic variations, with alternating zones of local stress concentration and stress unloading. Large differences in diagenetic and tectonic modification lead to the formation of stable medium-aperture fractures in flat sections, as well as extremely small-aperture residual fractures at local curved weak planes or large-aperture fractures induced by local tension. Consequently, their aperture distribution is the most dispersed.

In summary, the average fracture density differs markedly among the three lamina types: cross-laminated intervals have the highest density (138.5 fractures/m), followed by banded laminae (125.5 fractures/m), while inclined laminae show the lowest average density (104 fractures/m). This differentiated distribution is fundamentally controlled

by sedimentary heterogeneity and the spatial distribution of mechanical weak planes. Cross-laminated layers develop multiple sets of intersecting lamina interfaces, creating abundant fracture initiation sites and thus the highest fracture density. Banded laminae have continuous, flat bedding planes that support uniformly distributed fractures. In inclined laminae, undulating interfaces cause uneven stress distribution, resulting in localized fracture enrichment but lower overall average density.

5. Lamina-Associated Fracture Coupling Relationships and Storage–Permeability Control Mechanisms

5.1. Control of Lamina-Associated Fracture Development by Sedimentary Heterogeneity

Sedimentary heterogeneity is the core controlling factor governing the formation and development degree of lamina-associated fractures in tight reservoirs. This heterogeneity is essentially a direct manifestation of significant differences in material composition and microstructure between interlaminar layers [29]. Comparison of the 3D models of the three types of lamina-associated fractures with the interlaminar layer models in the study area reveals the following characteristics (Figure 8): banded lamina-associated fractures are nearly horizontal and parallel, with good continuity and uniform distribution, exhibiting significant bedding-parallel extension characteristics; the interlaminar layers have uniform thickness, strong continuity, and flat, stable bedding interfaces; the volume proportion of interlaminar layers is generally high, and fracture porosity shows small fluctuations with overall stability. The grayscale images of core sedimentary structures intuitively reproduce the primary sedimentary morphology of banded laminae, with flat horizontal bedding at the top.

Inclined lamina-associated fractures undulate synchronously with lamina interfaces, exhibiting an overall wavy directional arrangement. Fracture strike deflects with bedding, and local fracture density increases significantly. The interlaminar layers show gentle wavy undulations with rhythmic dynamic variations in layer thickness. Moreover, the fluctuation trend of the interlaminar layer volume proportion curve exhibits a clear synergistic response with lamina-associated fracture porosity, and the grayscale images of core sedimentary structures correspond to the primary morphology of inclined laminae. Cross-laminated lamina-associated fractures intersect and obliquely cut each other, with main fractures and secondary fractures interwoven into a network. This results in the most complex fracture network and optimal spatial connectivity. Cross-laminated interlaminar layers exhibit obvious bifurcation and intersection phenomena, with the strongest lithological association heterogeneity. The interlaminar layer proportion and lamina-associated fracture porosity show an overall inverse linkage: in intervals with reduced interlaminar layer proportion, the development degree of lamina-associated fractures increases significantly. The grayscale images of core sedimentary structures show inclined, intersected, and bifurcated laminae, which represent the original sedimentary response of cross-laminated laminae. Local strong dark fracture zones formed by tectonic modification are also visible.

Frequent lithological interbedding of argillaceous laminae and sandy layers results in significant differences in mechanical strength between the two lithologies. Higher lamina content leads to greater interlayer mechanical differences, making it easier to initiate lamina-associated fractures along interfaces. However, when lamina content is excessively high and the overall plasticity is too strong, compaction will compress and close primary fractures, thereby reducing fracture porosity. Therefore, the relationship between them is dynamic coupling rather than a simple linear correlation.

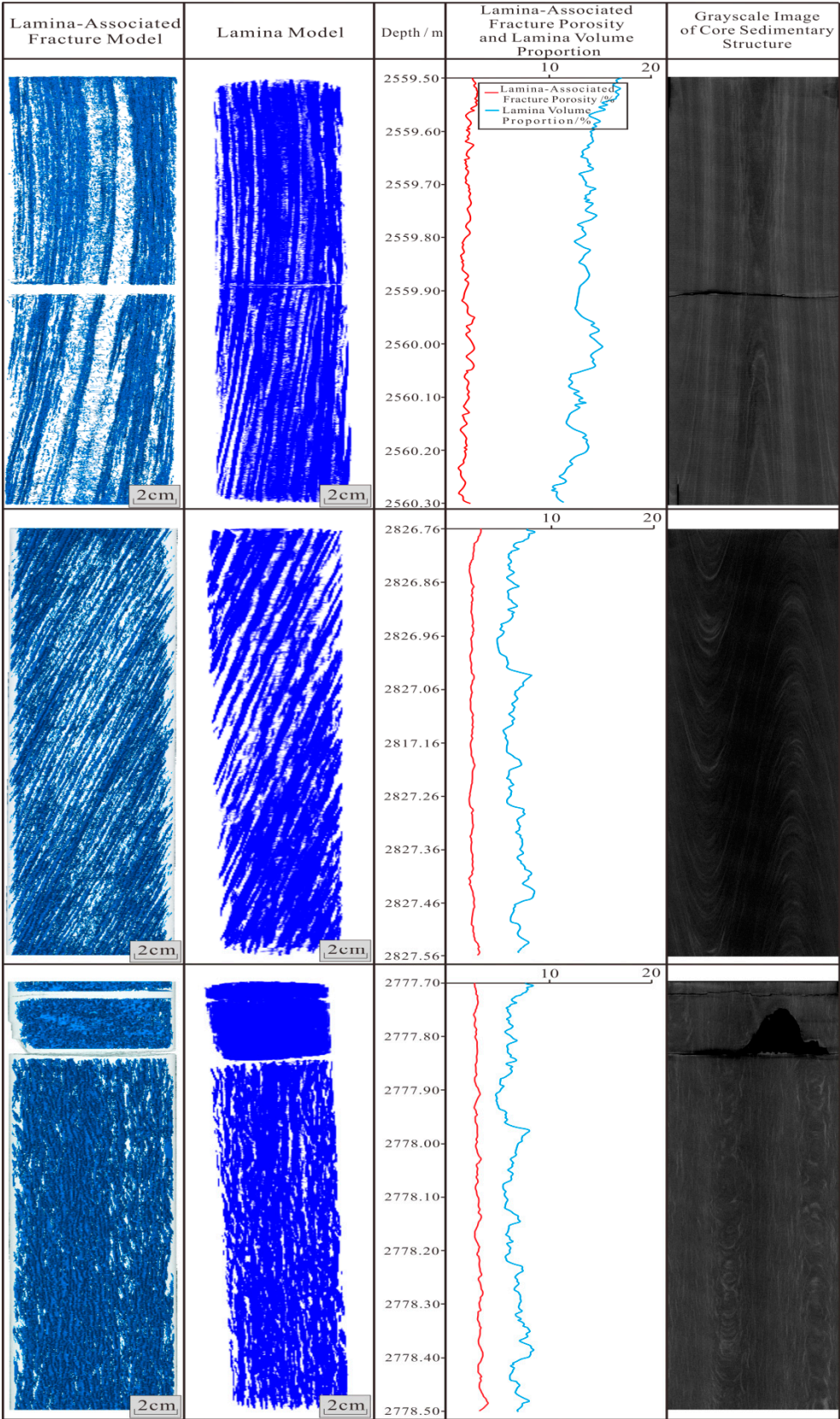


Figure 8. Lamina-associated fracture vs. lamina comparison by morphology in well Xi 119-19-39H (top to bottom: banded, inclined, cross-laminated).

Comparison of mean parameters (Figure 9) further reveals the coupling relationship between lamina morphology and the development of lamina-associated fractures:

cross-laminated laminae exhibit the highest interlamina layer volume proportion, fracture porosity, and fracture density among the three types, followed by banded laminae, while inclined laminae show the lowest values. Higher lamina content leads to more frequent sand–mudstone interbedding and more significant interlayer mechanical differences, facilitating the formation of high-porosity and high-density lamina-associated fracture networks along interfaces under diagenetic compaction and tectonic stress. Among them, cross-laminated laminae feature multiple sets of intersecting and cutting interfaces, resulting in more developed mechanical weak zones. Fractures readily interconnect and propagate, forming complex three-dimensional fracture networks. Banded laminae are flat and continuous with stable lithology, where fractures only develop along fixed bedding planes, showing uniform distribution but limited scale. Inclined laminae have frequently undulating interfaces and uneven stress distribution, leading to local fracture enrichment but weak overall connectivity.

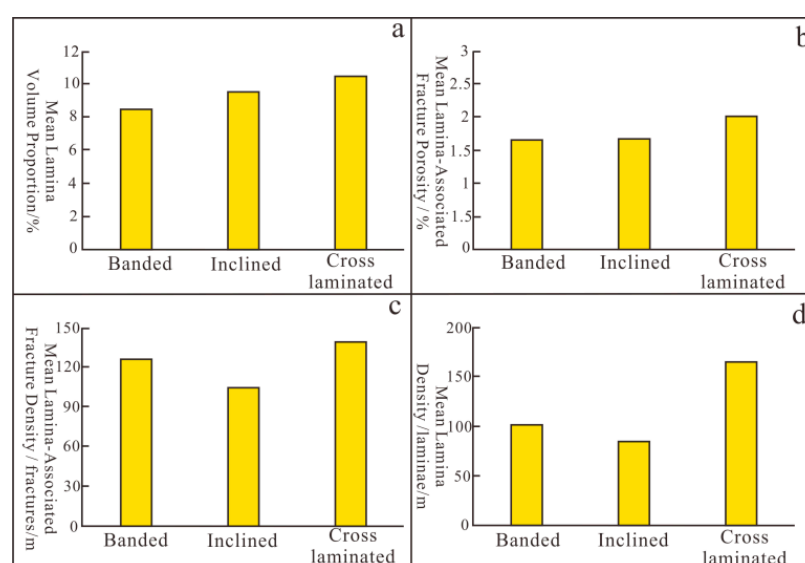


Figure 9. Mean parameter contrast of lamina heterogeneity and lamina-associated fractures by type ((a) Mean lamina volume; (b) Mean fracture porosity; (c) Mean fracture density; (d) Mean lamina density).

In summary, sedimentary heterogeneity directly dominates the development degree and distribution characteristics of lamina-associated fractures by controlling the material composition and structural differences between argillaceous laminae and sandy layers. Cross-laminated intervals, with optimal storage and seepage capacity of lamina-associated fractures, are high-quality sweet spot intervals for tight oil reservoirs in the study area. Inclined lamina intervals with local fracture enrichment can serve as secondary development targets. Banded lamina intervals are overall stable and suitable for horizontal well trajectory deployment to improve single-well production recovery.

5.2. Analysis of Pore–Lamina-Associated Fracture Coupling Relationships and Reservoir Structural Differences

5.2.1. Spatial Configuration Characteristics of Pores and Lamina-Associated Fractures

Based on high-precision 3D digital core reconstruction results, the spatial configuration relationships between matrix pores and lamina-associated fractures in the Chang 8 Member tight sandstone reservoir of the Xifeng Oilfield can be summarized into three typical forms: (1) lamina-associated fractures directly connect with intergranular/intragranular pores, forming “fracture–pore”-type high-efficiency seepage channels; (2) lamina-associated fractures develop directionally along lamina interfaces, acting as high-conductivity “bridges”

to connect isolated, disconnected pores into an integrated network; (3) lamina-associated fractures are partially filled with cement, forming a “semi-connected” transitional configuration with pores, which contributes significantly differently to reservoir seepage capacity. Under different lamina morphologies, the contact modes, connectivity ratios, and spatial distribution characteristics of pores and lamina-associated fractures are distinctly different, laying the microstructural foundation for subsequent differences in seepage behavior.

5.2.2. Pore–Lamina-Associated Fracture Coupling Patterns Under Different Lamina Morphologies

Figure 10 presents scatter plots of matrix porosity versus lamina-associated fracture porosity and fracture volume for the three types of laminae (banded, inclined, and cross-laminated), which clearly elucidates the differences in coupling patterns between matrix pores and lamina-associated fractures under different lamina morphologies.

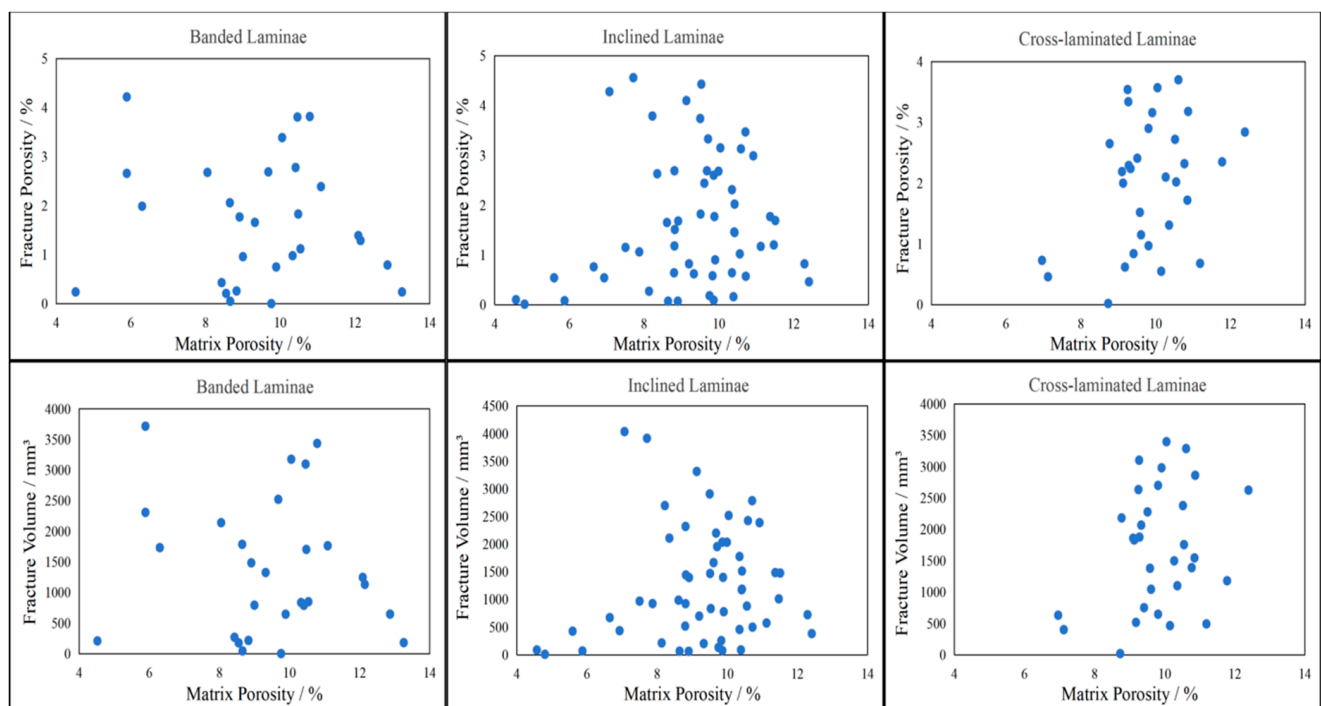


Figure 10. Scatter plots of matrix porosity vs. fracture-related parameters by lamina morphology.

No obvious linear relationship is observed between lamina-associated fracture porosity/fracture volume and matrix porosity in banded and inclined laminae. In banded laminae, some samples exhibit high fracture porosity and fracture volume when matrix porosity is low (4–8%); in samples with high matrix porosity (8–13%), fracture parameters show a wider distribution, including both low-fracture samples with underdeveloped fractures and samples with high fracture porosity and volume. In inclined laminae, the variation in fracture porosity and volume with matrix porosity exhibits a segmented characteristic: when matrix porosity is low (5–8%), fracture parameters are generally low; as matrix porosity increases to 8–12%, fracture parameters increase significantly with concentrated high-value points; when matrix porosity exceeds 12%, fracture parameters tend to decrease again. In cross-laminated laminae, matrix porosity is mainly distributed in the 7–13% interval, and fracture porosity and volume show a clear upward trend with increasing matrix porosity, with high-value points concentrated in the 8–12% matrix porosity range. Compared with banded and inclined laminae, the distribution of matrix pore and fracture parameters is more concentrated in cross-laminated intervals.

These distribution characteristics reflect the following: (1) Reservoir structural characteristics of banded laminae: The flat and continuous lamina interfaces have uniform mechanical properties, and the development of lamina-associated fractures is mainly controlled by bedding planes, relatively independent of the evolution process of matrix pores. The reservoir overall exhibits a homogeneous structure with “uniformly distributed matrix pores and linearly oriented lamina-associated fractures”, with weak coupling between the two. (2) “Segmented coupling” in inclined laminae: In the medium matrix porosity interval, sand–mudstone interbedding and sedimentary rhythm changes are the most frequent, and matrix pores and lamina-associated fractures develop synchronously, forming a storage system contributed by both matrix and fractures. In intervals with excessively low or high matrix porosity, the formation and propagation of lamina-associated fractures are restricted. (3) Cross-laminated laminae have high interlaminar layer volume proportion and frequent lithological interbedding, forming a large number of multi-directional mechanical weak interfaces. During diagenetic compaction and stress modification, matrix pores and lamina-associated fractures evolve synchronously. The formation and propagation of lamina-associated fractures not only contribute storage space themselves but also significantly improve the connectivity between matrix pores, ultimately forming a three-dimensional network structure with synergistic contribution from “matrix pores–lamina-associated fractures”, with the strongest coupling degree among the three types (Table 2).

Table 2. Pore–fracture coupling relationship and reservoir structural characteristics under different morphological laminae.

Lamina Morphology	Heterogeneity Degree	Fracture Development Degree	Pore–Fracture Coupling Pattern	Reservoir Structural Characteristics
Banded	Moderate	Moderate to strong	Independent development–weak coupling	Homogeneous structure with oriented fracture distribution
Inclined	Strong	Moderate	Segmented synergy–heterogeneous coupling	Strongly heterogeneous structure with local fracture enrichment
Cross-laminated	Very strong	Strong	Strong synergy–network coupling	Three-dimensional network structure with interconnected fractures

In summary, sedimentary lamina morphology governs the coupling patterns between matrix pores and lamina-associated fractures by controlling the frequency of lithological interbedding and the distribution of mechanical weak interfaces, thereby shaping distinct reservoir structures. The strong synergistic coupling pattern of cross-laminated laminae forms the optimal storage and seepage structure, making them high-quality sweet spot reservoirs for tight oil in the study area.

5.3. Correlation Analysis of Storage Space and Seepage Capacity in Multi-Level Coupled Systems

Tight sandstone oil reservoirs are universally characterized by well-developed lamina-associated fractures. These fractures, which develop along lamina interfaces, not only expand storage space but also constitute high-efficiency seepage pathways, making them key factors influencing tight hydrocarbon accumulation, single-well productivity, and development effectiveness [23,30]. In this study, representative sub-volumes were extracted

from the 3D models of the three types of lamina-associated fractures. Seepage simulations were performed using the Absolute Permeability Experiment Simulation module in PerGeos 2022.2. software to generate three-dimensional velocity fields. Velocity was correlated with streamline color via Illuminated Streamlines visualization and magnitude scalar mapping, and colored velocity field streamline distributions in the X and Z directions were finally obtained. In these maps, different colors represent distinct seepage velocities: red indicates high velocity, green indicates medium velocity, and purple indicates low velocity. Seepage simulation results confirm that fluids preferentially migrate along lamina-associated fractures and local fracture development zones, forming dominant flow pathways [31] (Figure 11).

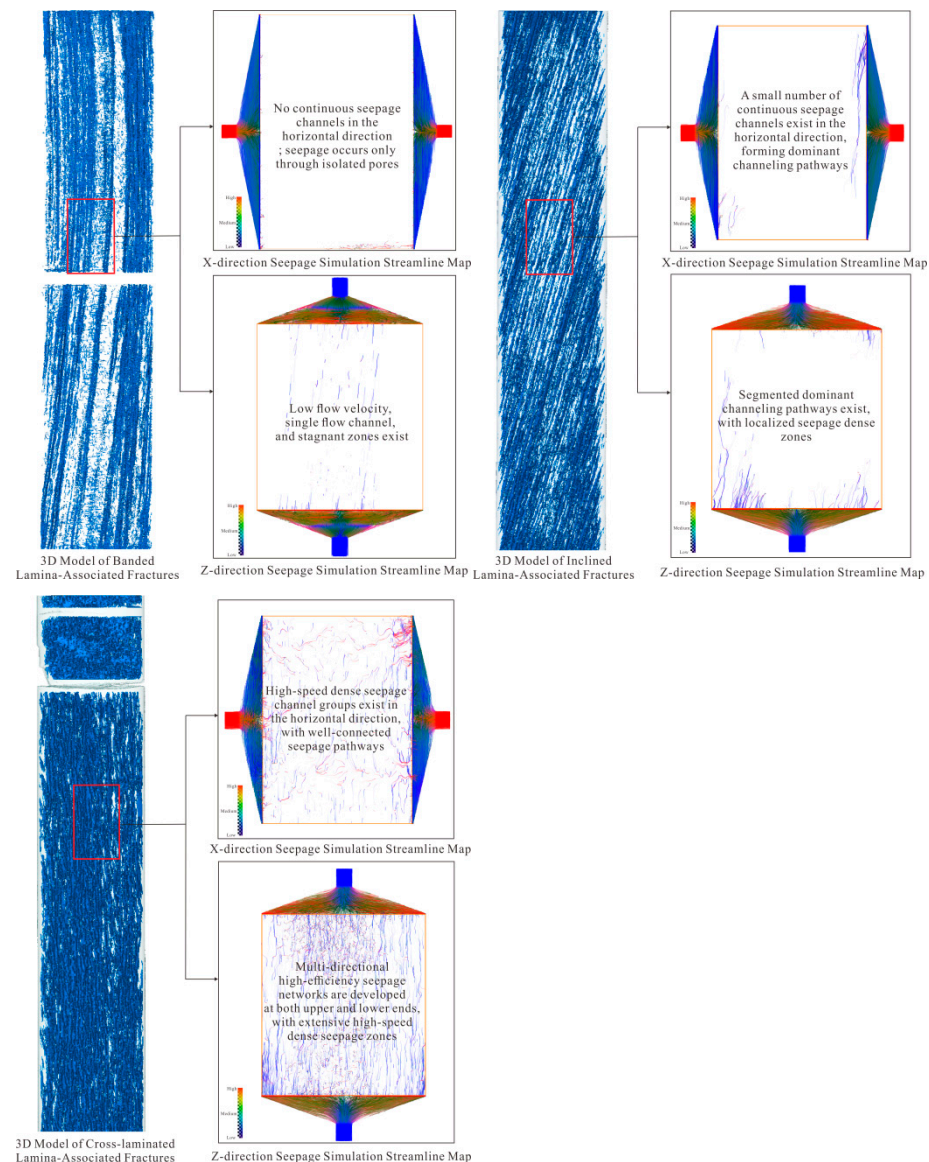


Figure 11. Seepage velocity streamlines in X and Z directions by lamina-associated fracture morphology.

In banded laminae, there are almost no continuous connected fracture channels in the X direction (horizontal). Fluids can only seep slowly through isolated pores in the matrix, with sparse and dispersed streamlines and extremely poor overall connectivity. In the Z direction (vertical), fluids mainly advance along a few bedding-parallel lamina-associated fractures forming single channels, with concentrated but slow streamline distribution. Obvious

streamline blank areas (stagnant zones) exist in the middle of the reservoir, indicating that some matrix pores cannot be swept by fluids, resulting in low sweep efficiency.

In inclined laminae, a small number of dominant channeling pathways formed by local fracture enrichment appear in the X direction (horizontal). Streamlines are concentrated along these channels, with significantly higher flow velocity than matrix pore seepage, and overall connectivity is better than that of banded laminae. In the Z direction (vertical), fluids form segmented dominant channels along fracture-enriched sections, with streamlines densely distributed in local areas. Alternating phenomena of distinct seepage dense zones and blank zones are observed, reflecting the strong heterogeneity characteristics.

In cross-laminated laminae, high-speed and dense seepage channel groups are formed in the X direction (horizontal), with streamlines interwoven in a network pattern. Fracture channels are widely connected with matrix pores, and overall seepage efficiency is significantly improved. In the Z direction (vertical), multi-directional high-efficiency seepage networks are developed at both the upper and lower ends. Streamlines cover the entire model space without obvious stagnant zones, and a large number of high-speed dense seepage areas exist, resulting in the highest fluid sweep efficiency.

Figure 12 presents comparative scatter plots of matrix porosity, fracture porosity/interlaminar layer volume percentage versus permeability for 5 core samples selected from each of the three lamina morphologies, revealing their differential contributions to seepage capacity.

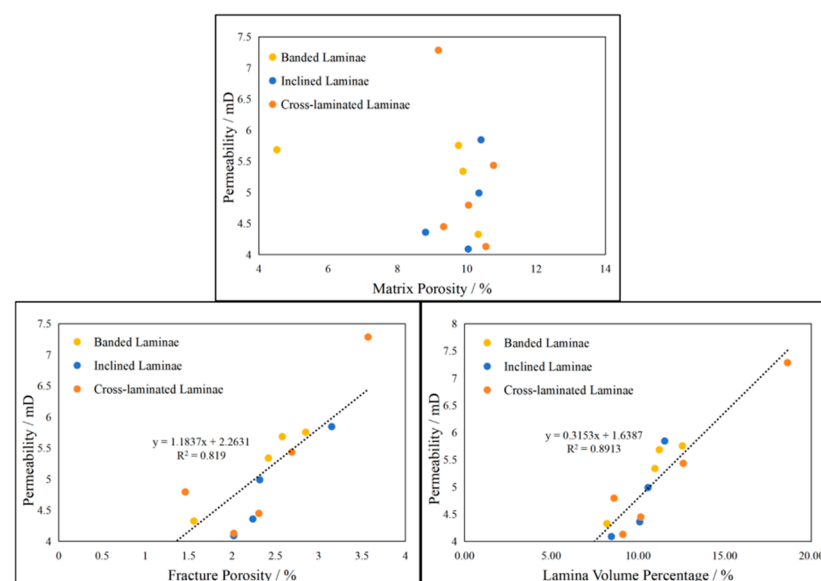


Figure 12. Correlation of matrix/ fracture porosity and interlaminar layer volume fraction with permeability by lamina morphology.

No obvious linear correlation is observed between matrix porosity and permeability. Even with similar matrix porosity, permeability varies significantly. This indicates that in tight sandstone reservoirs, matrix pores have extremely poor intrinsic connectivity and cannot effectively control fluid flow; permeability is not determined by matrix porosity. In contrast, fracture porosity and interlaminar layer volume percentage show a significant positive correlation with permeability. This demonstrates that lamina-associated fractures are the core factor controlling permeability, as they provide the primary pathways for fluid flow. The more developed the fractures are, the stronger the reservoir seepage capacity is. Furthermore, more frequent sand–mudstone interbedding and more abundant mechanical weak interfaces facilitate the development of lamina-associated fractures, thereby indirectly

enhancing permeability. Laminae do not directly provide seepage pathways but influence permeability by controlling fracture development.

Comparative analysis of pore structure, lamina-associated fracture development parameters, and seepage characteristics such as permeability reveals that reservoir seepage capacity has a weak correlation with matrix pores but is closely correlated with lamina-associated fracture-related parameters and connectivity. This finding reveals the essential characteristic of “connectivity structure dominates seepage capacity” in low-porosity and low-permeability sandstone reservoirs [32,33].

In summary, the more developed the lamina-associated fractures are and the higher their coupling degree with matrix pores is, the more complex the seepage pathways are and the higher the sweep efficiency is. Cross-laminated intervals are natural high-permeability “sweet spots”; banded lamina intervals require hydraulic fracturing stimulation to enhance fracture connectivity; and inclined lamina intervals need targeted stimulation of low-permeability intervals to improve displacement uniformity.

5.4. Methodological Limitations and Future Work

This study is based on 50 μm -resolution full-diameter CT scanning data, which has inherent limitations in fine matrix pore characterization. Due to the resolution constraint, submicron- to micron-scale matrix pores that account for the majority of total matrix pore volume cannot be effectively identified, resulting in systematic underestimation of absolute matrix porosity. The matrix porosity data in this paper only reflect the relative development degree of macro pores, and cannot fully represent the full-scale pore system of the reservoir.

In follow-up research, higher-resolution imaging techniques will be supplemented for typical core samples, including with micro-CT with a resolution of $\leq 5 \mu\text{m}$ and large-field-of-view SEM mosaic imaging. On the one hand, the total matrix porosity can be calibrated more accurately to quantitatively correct the underestimation degree of full-diameter CT data; on the other hand, the coupling relationship between micro-scale pores and lamina-associated fractures can be further explored, so as to improve the multi-scale characterization accuracy of tight reservoir pore–fracture systems.

6. Conclusions

Based on full-diameter CT core scanning technology, this study conducted a fine-scale 3D quantitative characterization of laminae and lamina-associated fractures of the Chang 8 Member tight sandstone from horizontal well X119-19-39H in the Xifeng Oilfield, Ordos Basin. The main conclusions for the study interval are as follows:

- (1) Laminae in the Chang 8 Member tight sandstone of the Xifeng Oilfield can be divided into three types: banded, inclined, and cross-laminated. Lamina-associated fractures are dominated by bedding-parallel fractures, with a small number of cross-bedding fractures accompanying cross-laminated laminae. Among them, cross-laminated lamina-associated fractures have the optimal fracture volume (average 1705.49 mm^3), density ($138.5 \text{ fractures/m}$), and fracture porosity (2.01%), making them the key lamina type controlling the development of reservoir “sweet spots”.
- (2) The development of lamina-associated fractures is jointly controlled by sedimentary heterogeneity and mechanical differences between laminae. There is a significant positive correlation between lamina volume proportion and fracture porosity ($R^2 = 0.8913$). Cross-laminated laminae have the strongest heterogeneity and readily form three-dimensional interconnected fracture networks; banded lamina-associated fractures develop linearly and uniformly; and inclined lamina-associated fractures exhibit local segmented enrichment characteristics.

- (3) The three types of laminae present distinct spatial coupling patterns between matrix pores and lamina-associated fractures: banded laminae show “independent development–weak coupling”, inclined laminae show “segmented synergy–heterogeneous coupling”, and cross-laminated laminae show “strong synergy–network coupling”. A significant spatial positive correlation exists between matrix porosity and fracture parameters in cross-laminated intervals, where matrix pores and lamina-associated fractures jointly form a three-dimensional interconnected storage–seepage system, with the optimal storage and seepage performance (maximum permeability reaching 7.3 mD).

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