

Advances and Trends in Reservoir Architecture Characterization of Continental Clastic Rocks: From Outcrop to Intelligent Modeling

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Abstract

As most continental oilfields in China enter the high water-cut stage, the distribution of remaining oil becomes highly dispersed and fragmented. Traditional reservoir characterization based on "layer-sand group" levels is no longer sufficient to meet the precision requirements for potential tapping. To address the challenges of sub-seismic resolution and inter-well uncertainty, this paper systematically reviews the theories, methods, and development trends of sandbody architecture characterization. First, the hierarchical architecture theories are synthesized, clarifying the correspondence between Miall's outcrop elements and subsurface flow units. Second, key characterization technologies are critically evaluated, highlighting the "Well-Seismic-Modeling" integration strategy. Specifically, the applications of seismic sedimentology in lateral boundary detection and the role of multiple-point statistics (MPS) in reproducing complex geological patterns are discussed. Furthermore, the emerging paradigm shift driven by Artificial Intelligence (AI), such as deep learning-based boundary recognition and GAN-based stochastic modeling, is elaborated. The review indicates that 3rd to 5th-order architectural interfaces (e.g., lateral accretion surfaces) act as dominant flow barriers controlling remaining oil distribution. Future research should focus on the construction of quantitative digital outcrop knowledge bases, the development of "Geology-Engineering" integrated dynamic models, and the deep fusion of AI with physical geological laws to achieve intelligent and precise reservoir descriptions.

Keywords

Reservoir Architecture, Continental Clastic Rocks, Remaining Oil, Seismic Sedimentology, Deep Learning, Geological Modeling.

1. Introduction

As the majority of continental oilfields in China enter the high water-cut or even ultra-high water-cut stage, the development environment has undergone fundamental changes. The distribution of remaining oil has transformed from continuous accumulations into highly dispersed and fragmented enrichments. Wu explicitly pointed out that under these conditions, the core challenge of geological engineering has shifted from structural exploration and scale expansion to the refined tapping of potential reservoirs within mature fields[1]. In this phase, the contradiction between injection and production becomes increasingly prominent, characterized by inefficient water circulation and low oil recovery rates.

Practical experience from field development indicates that traditional stratigraphic correlation and sedimentary facies analysis at the "layer-sand group" level are no longer sufficient to meet the precision requirements for modern reservoir characterization [2]. Conventional methods often simplify reservoir units into homogeneous "tanks," ignoring the complex internal heterogeneity caused by sedimentary processes. In reality, the intricate internal structures, particularly the baffling and barrier effects of hierarchical architectural interfaces (such as

lateral accretion surfaces in point bars), constitute the key geological factors that dictate fluid flow paths and restrict Enhanced Oil Recovery (EOR) efficiency [3]. Consequently, refined Reservoir Architecture research-which aims to dissect the internal anatomy and spatial connectivity of sandbodies-has become an inevitable requirement for stabilizing production and controlling water cut.

Theoretically, the concept of reservoir architecture originated from Miall's pioneering anatomy of fluvial outcrops [4]. He established a systematic "Architectural Element Analysis" method and a hierarchical bounding surface classification scheme (orders 0–6), which provided a genetic framework for decomposing chaotic clastic deposits into organized geometric bodies. This theory fundamentally changed the sedimentological understanding from simple facies modeling to quantitative structural analysis.

However, transposing architecture theories derived primarily from outcrops and modern deposits to deep subsurface reservoirs faces significant challenges. The primary obstacle lies in the "data resolution gap" and "solution non-uniqueness" [5]. Unlike outcrops that offer continuous 3D exposures, subsurface studies rely on sparse 1D well logs and low-resolution seismic data. Yue et al. [5] highlighted that identifying low-order interfaces (such as internal accretion layers) using only log curves is often ambiguous. Furthermore, in areas with sparse well spacing, accurately predicting the inter-well connectivity and the spatial extension of sandbody boundaries remains a "world-class" problem, as emphasized by Willis and Tang [6]. To address these technical bottlenecks and reduce geological uncertainty, the industry is witnessing a transition from qualitative description to quantitative and intelligent characterization. This paper systematically reviews the current status of reservoir architecture research, focusing on the evolution from traditional sedimentology to modern "Well-Seismic Integration" and "Stochastic Modeling." Furthermore, it critically evaluates the emerging application of Artificial Intelligence (AI), such as Deep Learning, in automating architecture identification. By synthesizing these advances, this review aims to provide a theoretical basis and practical guidelines for the precise description and intelligent development of mature continental reservoirs.

2. Deepening of Reservoir Architecture Theory: A Brief Review

Reservoir architecture refers to the geometry, scale, spatial distribution, and mutual stacking relationships of constituent units of different orders within a reservoir. From early sedimentological observation of outcrops to the current refined modeling of subsurface reservoirs, architecture theory has undergone a significant evolution from qualitative description to quantitative characterization.

2.1. Paradigm Shift: From "Outcrop Definition" to "Subsurface Application"

The core philosophy of architecture analysis originates from the hierarchical bounding surface theory proposed by Miall [4]. Based on modern fluvial deposits and ancient outcrop anatomy, Miall established the renowned classification system of "6-order bounding surfaces" and "9 architectural elements," deconstructing chaotic fluvial deposits into genetically related geometric bodies.

However, directly applying outcrop-based hierarchical schemes to subsurface reservoirs faces challenges regarding scale matching and data observability. While outcrop studies focus on the reconstruction of sedimentary processes, geological engineering (development geology) prioritizes the controlling effect of discontinuous interfaces on fluid flow [1]. In light of this, Wu et al. [1] proposed a "Subsurface Reservoir Architecture" classification scheme tailored for continental basins. This approach emphasizes interpreting architectural interfaces as "Flow Barriers" or "Flow Baffles". This paradigm shift marks the extension of architecture research

from the domain of pure sedimentology to reservoir engineering, where the core task shifts from identifying lithofacies to revealing the heterogeneous structures that control remaining oil distribution [3].

2.2. Key Hierarchies and Engineering Response

In the middle to late stages of waterflooding, architectural interfaces of different orders exert obvious cascading control effects on fluid movement. The current consensus divides fluvial reservoirs into the following hierarchical levels for dissection:

Channel Belt Complex (Miall Orders 5-6 / Wu Order 3): Macroscopically, this level controls the reservoir volume scale and regional connectivity.

Single Channel / Point Bar (Miall Order 4 / Wu Order 4): This is the primary target for current potential tapping in mature fields. Willis and Tang [6] pointed out that Lateral Accretion Surfaces (LAS) within point bars often develop muddy drapes, forming lateral impermeable boundaries that lead to the contradiction where "injection is ineffective, and production is water-free."

Accretion Unit (Miall Order 3 / Wu Order 5): This refers to units such as lateral accretion bodies within point bars or vertical accretion layers within braided bars. Yue et al. [5] established quantitative identification models for point bar accretion bodies, confirming that lower-order interfaces can evolve into preferential flow channels or local dead oil zones after long-term water flushing.

2.3. Quantitative Knowledge Base and Prototype Models

Due to the "tunnel vision" inherent in well data and the resolution limits of seismic data, establishing a Quantitative Knowledge Base derived from modern deposits and outcrops is the foundation for subsurface architecture characterization. Colombera et al. [7] compiled a global database containing thousands of fluvial architecture parameters and established empirical formulas for the width-to-thickness ratios of different river types. By introducing these Prototype Models, researchers can transform sparse 1D well data into geologically constrained 3D spatial prediction models, thereby significantly reducing the non-uniqueness of inter-well predictions [1, 7].

Table 1. Architecture Hierarchy pattern

Architecture Hierarchy (Wu / Miall)	Sedimentary Unit	Interface Characteristics	Main Architectural Elements	Spatial Scale (Approx.)	Development Geological Significance
Order 3 / Order 5-6	Channel Belt Complex	Regional scour surfaces; Extensive floodplain mudstones	Stacked channel belts	W:1000-5000 mH: 10-30 m	Inter-layer Interference Control: Determines the degree of well network control and layer series subdivision; controls the macroscopic sweep range of water flooding.
Order 4 / Order 4	Single Channel / Macroform	Basal scour surfaces; Abandoned channel fills	Point Bar Mid-channel Bar	W: 200-800 m H: 5-15 m	Planar Heterogeneity Control: The primary target for current remaining oil tapping. Interfaces can block lateral fluid flow, forming bypassed oil zones.
Order 5 / Order 3	Accretion Unit	Lateral Accretion Surfaces (LAS); Bar top drapes	Lateral Accretion Body Bar Internal Drapes	W: 20-100 m H: 1-5 m	Intra-layer Heterogeneity Control: Influences the advancing path of injected water. Muddy drapes lead to gravity segregation or fingering, forming "roof-like" remaining oil.
- / Order 1-2	Bedding Laminae /	Lamina bounding surfaces; Lithological abrupt interfaces	Parallel bedding; Cross-bedding	Scale: Centimeter level	Microscopic Pore Structure Control: Affects microscopic oil displacement efficiency and wettability; typically studied at the core scale.

3. Key Technologies for Architecture Characterization

The central challenge in subsurface architecture characterization lies in the "resolution gap" between sparse well data and low-resolution seismic data. To reconstruct 3D geological bodies accurately, current research generally follows a hierarchical constraint strategy: "Wells define vertical hierarchy, Seismic defines lateral boundaries, and Modeling reconstructs 3D entities."

3.1. Well-based Identification: Vertical Zonation and Inter-well Correlation

Well logs possess extremely high vertical resolution (centimeter scale) and remain the primary means for identifying single channels and internal accretion bodies (Orders 3–4).

Single-well Rock-Electricity Characterization: Different architectural elements exhibit specific response patterns on logs. For instance, lateral accretion layers in meandering river point bars typically manifest as dentated or recurring features on Gamma Ray (GR) or Resistivity curves. However, relying solely on curve morphology introduces non-uniqueness. Yue et al. [5] emphasized that identifying the "dip magnitude and azimuth" of accretion layers using Formation Micro-Imager (FMI) or Dipmeter logs is the most reliable method to determine the vector orientation of point bar progradation.

Multi-well Pattern Fitting: For inter-well connectivity, the "Elevation-Depth" fine correlation method is widely adopted [5]. This approach abandons traditional horizontal stratigraphic correlation. Instead, based on the geometric principle that "accretion layers incline towards the abandoned channel," it utilizes the dip angle (typically 2°–15°) identified in single wells to project and fit the extension trajectory of accretion layers between wells.

Critical Analysis: While well-based methods offer high vertical precision, they are highly dependent on well density. In areas where well spacing exceeds the scale of the sandbody (e.g., spacing > channel width), inter-well predictions often rely heavily on the subjective experience of the geologist (Expert Bias) [6].

3.2. Seismic Sedimentology and Frequency Division Techniques

Seismic data provides critical lateral continuity information, compensating for the "tunnel vision" of well data. The focus has shifted from structural interpretation to lithological parameter inversion.

Seismic Sedimentology: Zeng [8] proposed the theory of seismic sedimentology, utilizing 90° phase rotation to transform seismic traces into pseudo-lithologic profiles. By extracting Stratal Slices within an isochronous stratigraphic framework, this method can clearly depict the plan-view morphology (e.g., sinuosity, width) of paleo-channels, providing deterministic constraints for the lateral boundaries of channel belts (Order 3).

Frequency Division (Spectral Decomposition): To address the limit of seismic vertical resolution (tuning thickness, typically ~10-20m), Dong et al. [9] applied spectral decomposition techniques. High-frequency volumes (e.g., 40-60 Hz) are more sensitive to thin interbeds and internal discontinuities. By fusing different frequency components (RGB Blending), researchers can semi-quantitatively identify the boundaries of single channels or even large-scale point bars (Order 4).

Critical Analysis: Despite these advances, seismic methods are fundamentally limited by the physical bandwidth of seismic waves. They are generally unable to directly resolve internal muddy drapes (Order 5, thickness < 1m) within point bars, necessitating calibration with well data [8].

3.3. Deterministic and Stochastic Modeling

3D geological modeling is the pivotal link transforming 2D geological understanding into 3D digital entities. Wu et al. [1] emphasized the transition from "interpolation-based" to "geological pattern-based" modeling.

Object-based Modeling: This method treats geological bodies (e.g., channels, levees) as "objects" with specific geometric parameters (width, thickness, sinuosity). Algorithms simulate the depositional process by placing these objects into the model space until they match well data. It excels at reproducing crisp channel geometries but struggles to condition strictly to dense well data [7].

Multiple-Point Statistics (MPS): To overcome the limitations of traditional two-point variograms in describing curvilinear features, Strebelle [10] introduced Training Images (TI). MPS algorithms scan TIs (derived from modern satellite images or conceptual models) to capture multi-point probability patterns. This allows the model to reproduce complex heterogeneous features, such as the cross-cutting relationships of meandering channels and oxbow lakes, which are difficult to capture with variogram-based methods.

Critical Analysis: MPS is currently considered the most promising method for complex architecture modeling. However, its accuracy heavily depends on the representativeness of the Training Image. If the TI fails to capture the actual subsurface geological variation (non-stationarity), the resulting model may be geologically unrealistic [10].

4. Sandbody Stacking Patterns and Their Spatial Distribution Characteristics

Sandbody stacking patterns refer to the topological overlapping relationships and geometric arrangements of individual architectural units in three-dimensional space. These patterns serve as a bridge connecting microscopic architectural elements with macroscopic reservoir heterogeneity, directly determining reservoir connectivity and fluid flow paths during waterflooding.

4.1. Refined Classification and Characteristics of Stacking Patterns

Based on the degree of amalgamation, contact relationships, and connectivity properties between sandbodies, stacking patterns in continental fluvial reservoirs are primarily classified into four categories (Table 2):

Isolated Pattern: Individual sandbodies are completely surrounded by extensive floodplain mudstones without mutual contact. This pattern typically develops under high accommodation conditions ($A/S > 1$), resulting in poor static connectivity.

Laterally Amalgamated Pattern: Sandbodies overlap laterally with relatively stable vertical thickness. Commonly found in meandering river point bar complexes, this pattern offers good lateral connectivity but is often hindered by lateral muddy drapes.

Vertically Amalgamated Pattern: Late-stage channels deeply incise into early-stage sandbodies, forming a "multi-story" structure with high vertical overlap. This pattern exhibits excellent connectivity and is prone to forming vertical "thief zones" during development.

Complex Amalgamated Pattern: Intense incision occurs both vertically and laterally, forming sheet-like sandbodies with extremely complex internal architectural interfaces.

Table 2. Classification and Development Geological Characteristics of Sandbody Stacking Patterns

Stacking Pattern	Spatial Geometric Features	Connectivity Evaluation	Typical Log Facies Features
Isolated	Sandbodies encased in mudstone; no mutual contact	Extremely poor (static disconnection)	Isolated finger-shaped; single-peak bell shape
Lateral	Lateral overlap; thin vertical thickness	Good lateral; vertical baffling	Composite bell shape; serrated multi-peak
Vertical	Late-stage incision into early sandbodies	Excellent (prone to thief zones)	Thick box-shape (with micro-kicks)
Complex	Intense vertical/lateral amalgamation; sheet-like	Overall connected; high heterogeneity	Amalgamated box-shape; funnel-box combination

4.2. Deep Genesis and Controlling Factors of Stacking Patterns

The spatio-temporal evolution of sandbody stacking is controlled by the dynamic coupling of "Source-Sink-Flow" factors. The core controlling factors include:

4.2.1. Sequence Constraint of Base-level Evolution and A/S Ratio

The ratio of accommodation (A) to sediment supply (S), determined by base-level changes, is the primary control. When $A/S < 1$ (lowstand or base-level falling), fluvial incision intensifies, favoring vertically amalgamated patterns. When $A/S > 1$ (highstand or base-level rising), mudstone preservation increases, and sandbodies become isolated [12].

4.2.2. "Source-to-Sink" Control of Sediment Supply and Flux

Recent studies emphasize the decisive role of source-area characteristics on basinward sandbody distribution. The sediment supply rate (Q_s) directly determines the filling efficiency. Under high sediment flux, sandbodies may physically contact even if A/S is large, creating "pseudo-lowstand" amalgamated features [13].

4.2.3. Physical Constraints of Microfacies and Hydrodynamic Processes

Different sedimentary microfacies reflect varying hydrodynamic energy levels. Meandering river point bars are dominated by lateral migration, resulting in lateral stacking. Braided river bars are dominated by vertical and downstream accretion; high-energy flood scouring often forms large-scale vertically amalgamated box-shaped sandbodies. 4.2.4 Regulation by Palaeotopography, Tectonics, and Climate Fluctuations Uneven tectonic subsidence in rift basins leads to high-density stacking in depocenters. Furthermore, climate-driven wet-dry cycles control seasonal discharge. High-frequency floods during arid periods favor high-energy incision and thick vertical stacking, while stable flow during humid periods leads to more regular stacking patterns [14, 15].

4.3. Research Frontiers and Innovations (2021-2025)

4.3.1. Intelligence-Driven Automated Identification

Traditional identification of stacking patterns using log facies (box/bell shapes) suffers from subjective non-uniqueness. Recent studies have introduced 1D-CNN and Transformer models to utilize long-short-term dependencies in well logs for automated recognition of amalgamation interfaces. AI models show significant advantages in capturing "micro-kicks" within vertically amalgamated sequences [11].

4.3.2. Quantitative Characterization via Topological Connectivity

By introducing Graph Theory and Topology, stacked sandbodies are abstracted into "nodes" and "edges." Using metrics such as topological entropy and connectivity probability matrices, researchers can quantitatively describe connectivity quality, overcoming the limitations of traditional Net-to-Gross (N/G) ratios [14].

4.3.3. Architecture Prototype Knowledge Bases via Digital Outcrops

Millimeter-scale digital outcrop models acquired through UAV oblique photography and LiDAR provide precise parameters for stacking patterns. By establishing quantitative knowledge bases containing amalgamation angles and width-to-thickness ratios, researchers can provide prior probability constraints for modeling in un-drilled or sparse-well areas [17].

5. Control Mechanisms and Engineering Practices of Reservoir Architecture on Remaining Oil

In the late stage of oilfield development, characterized by "ultra-high water cut and highly structural heterogeneity," reservoir architecture has become the fundamental factor determining fluid seepage trajectories and the distribution patterns of remaining oil. This chapter focuses on how architectural elements control remaining oil through physical barriers and seepage anisotropy, concluding with corresponding engineering strategies.

5.1. The "Baffling-Guiding" Mechanism of Architectural Interfaces on Fluid Flow

Architectural interfaces of orders 3–5 (such as lateral accretion surfaces, bar-top drapes, and scour surfaces) are often associated with muddy drapes or diagenetic cementation, acting as discontinuous flow barriers or baffles. Seepage Anisotropy: Architectural units possess significant internal orientation. Research indicates that the permeability parallel to the lateral accretion surface and perpendicular to it can differ by 2 to 3 orders of magnitude [15]. Flow Bypassing and Fingering: Driven by pressure gradients, injected water tends to bypass muddy baffles and breakthrough along high-energy channels (e.g., the coarse-grained basal part of a bar). This "seepage short-circuiting" caused by architecture leads to large unswept areas above or behind the baffles.

5.2. Remaining Oil Accumulation Patterns Based on Architecture

Synthesizing production anatomy data from the past five years, remaining oil in continental fluvial reservoirs controlled by architecture can be summarized into three typical patterns:

5.2.1. "Eaves-shaped" Remaining Oil within Point Bars

In meandering river point bar reservoirs, lateral accretion surfaces (LAS) incline toward the abandoned channel [16]. Due to gravity segregation, injected water tends to advance along the bottom. The LAS act like "umbrellas," shielding the upward sweep of injected water. Consequently, crude oil accumulates in the "dead zones" beneath the accretion surfaces, forming an "eaves-shaped" distribution [17].

5.2.2. "Bar-top Baffle" Remaining Oil within Braided Bars

Horizontal bar-top drapes within braided bars divide thick sandbodies into multiple relatively independent flow units. Under long-term flushing, the lower units become heavily flooded due to higher permeability, while the upper units remain oil-rich due to insufficient displacement drive caused by the drapes.

5.2.3. "Stagnant Boundary" Remaining Oil in Stacking Zones

At the lateral stacking boundaries of early and late-stage channels, muddy rip-ups or physical mutations often occur. When the injection-production orientation is parallel to the stacking

zone, fluid tends to flow along the channel axis, creating stagnant zones with extremely low flow velocities at the edges of the stacking bodies [18].

Table 3. Remaining Oil Pattern

Remaining Oil Pattern	Control Hierarchy	Primary Cause	Identification Sign
Eaves-shaped	Order 5 (LAS)	Inclined shielding + Gravity segregation	Log "kicks"; RFT pressure gradient mutation
Attic Oil	Order 4-5	Gravity segregation in fining-upward sequences	High water cut at the basal production interval
Isolated Lens	Order 3-4	Static disconnection; Imperfect well pattern	No response in dynamic monitoring

5.3. Fine Potential Tapping Engineering Strategies under Architecture Constraints

Addressing the aforementioned architecture-controlled oil patterns, modern geological engineering advocates for an integrated strategy of "interpreting static via dynamic, and guiding dynamic via static":

- Horizontal Well Crossing Accretion Layers:** In point bar reservoirs, horizontal wells are designed to be perpendicular to the strike of lateral accretion surfaces. By "penetrating" multiple accretion bodies, these wells can simultaneously tap several remaining oil enrichment zones previously isolated by baffles [19].
- Dynamic Adjustment of Injection-Production Orientation:** By altering the injection-production azimuth to form a 45°–90° angle with the lateral accretion surfaces or stacking zones, injected water is forced to cross architectural interfaces, thereby significantly improving the sweep coefficient.
- Intelligent Profile Control Under Architecture Constraints:** Utilizing "thief zones" identified by refined architectural models, chemical plugging agents are injected near the wellbore to seal high-permeability channels formed by vertical stacking.

6. Main Challenges Faced Currently

In the context of brownfield redevelopment or low-cost development, geologists frequently face a scarcity of core data, image logs, and high-quality seismic volumes. Consequently, fine characterization of sandbody stacking patterns relying solely on Gamma Ray (GR) logs has become a challenging yet unavoidable task.

6.1. Limitations and Ambiguity of Traditional Methods

Traditional electrofacies analysis relies heavily on the qualitative identification of log shapes (e.g., box-shaped, bell-shaped). However, literature indicates that characterizing internal structures of thick sandbodies using a single GR curve suffers from significant "non-uniqueness." For instance, vertically amalgamated composite channels often manifest as massive box-shaped profiles on GR logs. Without sufficient mud intraclasts or calcareous cementation at the scour surfaces, these internal interfaces are easily misinterpreted as single-stage channels. This resolution limit hinders the accurate depiction of complex stacking patterns.

6.2. Signal Processing: From "Shape" to "Frequency"

To transcend the limits of visual interpretation, researchers have introduced mathematical transformation techniques to mine hidden information within GR curves.

Wavelet Transform: Leveraging the time-frequency localization properties of Continuous Wavelet Transform (CWT), GR curves can be decomposed into energy spectra of different scales. Studies have shown that abrupt physical property changes at amalgamation interfaces manifest as distinct modulus maxima or singularities on wavelet coefficient maps, effectively revealing the internal periodicity within "box-shaped" sands.

INPEFA Technology: The Integrated Prediction Error Filter Analysis (INPEFA) curve, based on maximum entropy spectral analysis, is highly sensitive to sedimentary cycles. It can identify micro-scale retrogradational/progradational inflection points that are imperceptible on conventional curves, providing a quantitative basis for delineating single architectural elements.

6.3. AI-Driven Sequence Feature Extraction

With the advent of deep learning, data-driven recognition methods have emerged as a new trend. Unlike human interpretation, algorithms such as 1D Convolutional Neural Networks (1D-CNN) and Long Short-Term Memory (LSTM) networks treat GR curves as time-series data. They can automatically extract latent non-linear features (e.g., subtle fining-upward trends or serrated patterns). Well-trained AI models have demonstrated recognition accuracies exceeding 85% for stacking patterns using only GR inputs, proving that single curves indeed contain sufficient "fingerprint information" for architectural characterization.

Although constrained by the lack of multi-source data integration, characterizing sandbody stacking patterns using solely GR logs is theoretically and practically feasible through the application of frequency-domain analysis and deep learning. The key lies in the paradigm shift from qualitative "shape observation" to quantitative "signal mining."

7. Development Prospects

As most continental oilfields in China enter the high water-cut or ultra-high water-cut stage, traditional characterization methods are no longer sufficient to meet the requirements for fine potential tapping. To address the challenges of inter-well uncertainty and sub-seismic resolution, future research on reservoir architecture will primarily focus on the following four frontier directions:

(1) Deep Fusion of AI and Generative Modeling Traditional two-point geostatistics and multiple-point statistics (MPS) face challenges in computational efficiency and training image stationarity. Future directions include:

Application of Generative AI: Utilizing Generative Adversarial Networks (GANs) (such as Pix2Pix or CycleGAN) to directly "translate" seismic slices into sedimentary facies maps. GANs can rapidly generate thousands of geological realizations that conform to complex stacking rules and automatically fill inter-well uncertainty regions with realistic geological patterns.

Deep Learning-Driven Identification: Employing models like 1D-CNN (Convolutional Neural Networks) and LSTM (Long Short-Term Memory) to mine non-linear features in well logs (such as micro-kicks), enabling the automated recognition of stacking patterns and architectural interfaces with an accuracy exceeding 85%.

(2) Integration of "Geology and Engineering" for Dynamic Modeling The research focus will shift from purely static geological description to dynamic engineering response analysis.

Dynamic-Static Integration Strategy: Advocating a comprehensive strategy of "interpreting static via dynamic, and guiding dynamic via static," using dynamic production data to inversely validate static models.

Refined Engineering Measures: Formulating specific engineering measures for different remaining oil patterns (e.g., "eaves-shaped" remaining oil within point bars or "baffle-

controlled" remaining oil at bar tops), such as designing horizontal wells traversing lateral accretion layers or adjusting injection-production orientations to improve sweep efficiency.

(3) Construction of Quantitative Digital Outcrop Knowledge Bases To overcome the "tunnel vision" of well data and the resolution limits of seismic data, establishing quantitative prior knowledge bases is crucial.

Millimeter-Level Modeling: Using UAV oblique photography and LiDAR to acquire millimeter-level digital outcrop models.

Parametric Constraints: Building quantitative knowledge bases containing parameters such as amalgamation angles and width-to-thickness ratios to provide prior probability constraints for modeling in un-drilled or sparse-well areas.

4 Advanced Signal Processing for Data Mining In mature oilfields lacking cores and image logs, mining hidden information from single GR logs is the inevitable path.

Frequency Domain Analysis: Utilizing Continuous Wavelet Transform (CWT) to decompose GR curve spectra and identify abrupt physical property changes at amalgamation interfaces.

INPEFA Technology: Applying INPEFA curves to identify microscopic sedimentary cycles and progradational/retrogradational inflection points that are imperceptible on conventional curves.

8. Conclusion

In summary, the characterization of continental clastic reservoir architecture is at a critical transition period from "qualitative pattern description" to "quantitative intelligent modeling."

(1) Shift in Core Contradiction: As oilfield development enters late stages, the distribution of remaining oil has transformed from continuous sheets to highly dispersed and fragmented accumulations. Traditional stratigraphic correlation at the "layer-sand group" level can no longer meet production needs; research must penetrate to the level of 3rd to 5th-order architectural interfaces (e.g., lateral accretion surfaces, bar-top drapes).

(2) Controlling Role of Architecture: Architectural interfaces form fluid barriers or baffles through muddy drapes or diagenetic cementation, causing severe permeability anisotropy (permeability differences can reach 2-3 orders of magnitude). This is the fundamental geological factor controlling waterflooding sweep efficiency and remaining oil enrichment.

(3) Technical Evolution Path : Hierarchical Constraints: Following the strategy of "Wells define vertical hierarchy, Seismic defines lateral boundaries, and Modeling reconstructs 3D entities". Modeling Strategies: Object-based methods are recommended for isolated sandbodies, while Multiple-Point Geostatistics (MPS) or Generative AI are recommended for complex amalgamated sandbodies.Characterization of Non-stationarity: Modeling must characterize spatial non-stationarity through probability cubes and rotation vector fields to reflect changes in sedimentary environments.

Ultimately, future reservoir architecture research will be dedicated to achieving the deep fusion of artificial intelligence with physical geological laws, constructing dynamic models integrated with "Geology-Engineering," and thereby realizing the intelligent and precise description of mature continental reservoirs.

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