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Fine Characterization and Residual Oil Exploitation of Shallow-Water Delta Sand in Oilfield B of Bohai Bay Basin

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Abstract

In Oilfield B of the Bohai Bay Basin, the shallow-water delta sandbody reservoirs are thin and exhibit rapid lateral changes. Local incised superposition results in complex oil-water relationships within the sandbodies and uneven plane injection-production response, which restricts the efficient tapping of remaining oil. Based on data such as drilling cores, geochemical analysis, well logging, and seismic data, the sedimentary characteristics of the lobate shallow-water delta are determined. Through seismic forward modeling, the seismic waveform characteristics of different sand body stacking patterns are summarized to guide the fine description of composite sand body stacking patterns and single-stage sand body plane distribution patterns. The results show that: by using identification markers such as the discontinuous, superimposed, and elevation difference characteristics of event axes on inverted seismic profiles, as well as the variation zones of planar seismic attributes, 2 phases of composite channels can be divided. Five types of sandbody contact patterns were summarized, including discrete contact, lateral cutting contact, natural levee connection, vertical aggradation superimposition, and composite superimposition. Combined with the results of fine characterization of sand bodies, based on the single-phase channel and river-bar lobes, the remaining oil distribution law is summarized, the oil-water relationship and remaining oil distribution of the river-bar composite sand body are jointly controlled by the cutting interface of the sand body and the rhythm pattern of the composite sand body, and the potential tapping strategies such as improving the single-phase channel well pattern, river-bar lobes well pattern reconstruction and local encryption are proposed. The successful implementation of 24 adjustment wells and the successful production of 100 m^3/d from 9 new adjustment wells demonstrates that the fine characterization method and resulting residual oil predictions are reasonable and credible, and provide reference for the development, production and potential mining of similar oilfields.

Keywords

Shallow Water Delta Front, Fine Characterization of Sand Body, Sand Body Contact Style, Residual Oil Prediction, Bohai Bay Basin

1. Introduction

Shallow-water delta sandbodies are widely distributed in the Mesozoic-Cenozoic strata of continental depression lake basins in China, and they are not only a research hotspot in modern sedimentology but also a key target for lithologic hydrocarbon reservoir exploration. Recent exploration practices in the Bohai Oilfield have confirmed that more than ten large-medium-sized oil and gas fields have been successively discovered by targeting shallow-water delta sandbodies in the Lower Member of the Neogene Minghuazhen Formation, making this a highlight of hydrocarbon exploration in the region with broad prospects. At present, fine research on shallow-water delta sandbodies mainly relies on methods such as dense well patterns, outcrops, modern sedimentation, and flume experiments, enabling dissection accuracy down to the single-channel level (Cai et al., 2016; Zhang et al., 2014; Zhu et al., 2008; Dai et al., 2007; Feng et al., 2012; Sun et al., 2016; Lou et al., 2004; Sun et al., 2015; Zhao et al., 2014; Jin et al., 2014). Shallow-water deltas typically form in open lake basins characterized by relatively stable tectonics, gentle terrain, slow overall basin subsidence, shallow water, suitable paleoclimate, frequent lake-level fluctuations, and sufficient sediment supply. Due to the numerous controlling factors affecting the sedimentary setting, dynamic mechanisms, and spatial distribution of sedimentary facies belts of shallow-water deltas, their sedimentary models are correspondingly complex and variable. Scholars at home and abroad have conducted extensive and in-depth studies on shallow-water deltas in different regions, focusing on aspects such as formation dynamics, microfacies characteristics, internal structure, genetic mechanisms, and sedimentary models (Zou et al., 2008; Yin et al., 2012; Zhang et al., 2010; Postma, 1990; Gilbert, 1890). For example, Liu Changni and Wu Shenghe et al., clarified the architectural characteristics and formation mechanisms of the shallow-water delta-offshore bar system in lake basins by integrating sedimentary numerical simulation results from Delft3D. Xu Zhenhua et al., took the Rimaozhou Delta of Poyang Lake as a case study and revealed the sedimentary architecture and formation mechanism of dendritic sandbars in the river-dominated shallow-water delta front by synthesizing satellite images, ground-penetrating radar data, shallow boreholes, and sedimentary numerical simulation data; these dendritic sandbars are formed by the splicing of multiple bifurcating and intersecting finger-shaped sandbars, presenting a "river flowing on the bar" river-bar combination relationship. Heng Yong et al., studied the internal structural characteristics of channel sandbodies in the

Middle Jurassic Shaximiao Formation of the Zhongjiang Gas Field and their influence on gas-water distribution, established corresponding architectural models, and analyzed gas-water distribution characteristics under different channel architectural models.

Therefore, a single typical sedimentary model or sandbody contact pattern cannot uniformly describe the spatial distribution of shallow-water delta sandbodies controlled by complex factors; instead, a comprehensive consideration of dominant factors and the actual distribution characteristics of sandbodies is required. However, offshore oilfields face challenges such as scarce drilling data and relatively large development well spacing, which cannot meet the requirements of reservoir architecture characterization technologies relying on dense well patterns in onshore oilfields. Thus, offshore studies mainly apply theories related to seismic sedimentology and use seismic attribute analysis methods to investigate the distribution patterns of inter-well sandbodies under large well spacing conditions.

Shallow-water delta sandbodies in the Bohai region generally have shallow burial depths, allowing seismic data to achieve good reservoir description. Nevertheless, local well-seismic response discrepancies exist: some development wells drilled in weak amplitude zones encounter thick reservoirs, and production dynamics between injection and production wells show injection-production responses. Currently, the dissection accuracy of shallow-water delta sandbodies in the study area is mostly limited to the composite sandbody level, while research on single-channel sandbody superimposition patterns-which affect reservoir connectivity and waterflooding development efficiency-remains relatively weak. Fine reservoir characterization is therefore necessary to guide in-depth potential tapping in the region.Accordingly, this study selects Oilfield B in the Bohai Bay Basin as the research target. Under the guidance of a reasonable shallow-water delta sedimentary model, it strengthens well-seismic integration and explores a fine dissection method for shallow-water delta sandbodies that achieves high coupling between seismic forward modeling and fine sandbody characterization. The aim is to realize fine characterization of the internal structure and incised superposition interfaces of complex channel sandbodies, thereby providing reliable geological basis for oilfield development and production.

2. Overview of the Study Area

The study area is located in the southern Bohai Sea, within a "depression-internal uplift" tectonic belt at the junction of the Bozhong Depression, Shanan Depression, Bonan Uplift, and Shaleitian Uplift. Surrounded by three major hydrocarbon-generating depressions (Shanan, Huanghekou, and Bozhong), it is one of the most favorable areas for hydrocarbon accumulation in the Bohai Sea (**Figure 1**). From top to bottom, the strata in the area are: the Quaternary Pingyuan Formation, the Neogene Minghuazhen Formation and Guantao Formation, and the Paleogene Dongying Formation. The main oil-bearing interval is the Lower Minghuazhen Formation (Figure 1). The reservoir rocks are predominantly very fine-fine-grained and medium-fine-grained lithic arkose, with low compositional maturity, moderate-good sorting, and subangular-subrounded grain shapes. The rocks have well-developed pores (mainly intergranular pores) with good connectivity. The sedimentary environment is that of a shallow-water delta, which can be further subdivided into bar-type shallow-water delta and distributary channel-type shallow-water delta. Based on changes in sedimentary base level and stratigraphic structure: During the early sedimentary stage of the Lower Minghuazhen Member, the sedimentary base level rose, increasing accommodation space. Fluvial processes were significantly stronger than lacustrine processes, leading to the development of channel-type shallow-water deltas. Sandbodies were distributed in strip-like patterns on the plane, with continuous and stable sedimentation along the channel direction. The development model mainly adopted alternating injection-production wells and well deployment along the channels. During the late sedimentary stage of the Lower Minghuazhen, the sedimentary base level fell, and lake water backwater effects became prominent. Lacustrine processes exceeded fluvial processes, resulting in the development of bar-type shallow-water deltas. Sandbodies were widely distributed with good vertical superimposition. In the early development stage, the model of commingled injection and production using directional wells was mainly adopted. However, affected by horizontal and vertical incised superposition interfaces within the sandbodies, problems such as interlayer interference in directional wells and uneven horizontal injection-production response have become increasingly prominent. There is an urgent need to deepen geological understanding to guide remaining oil tapping.

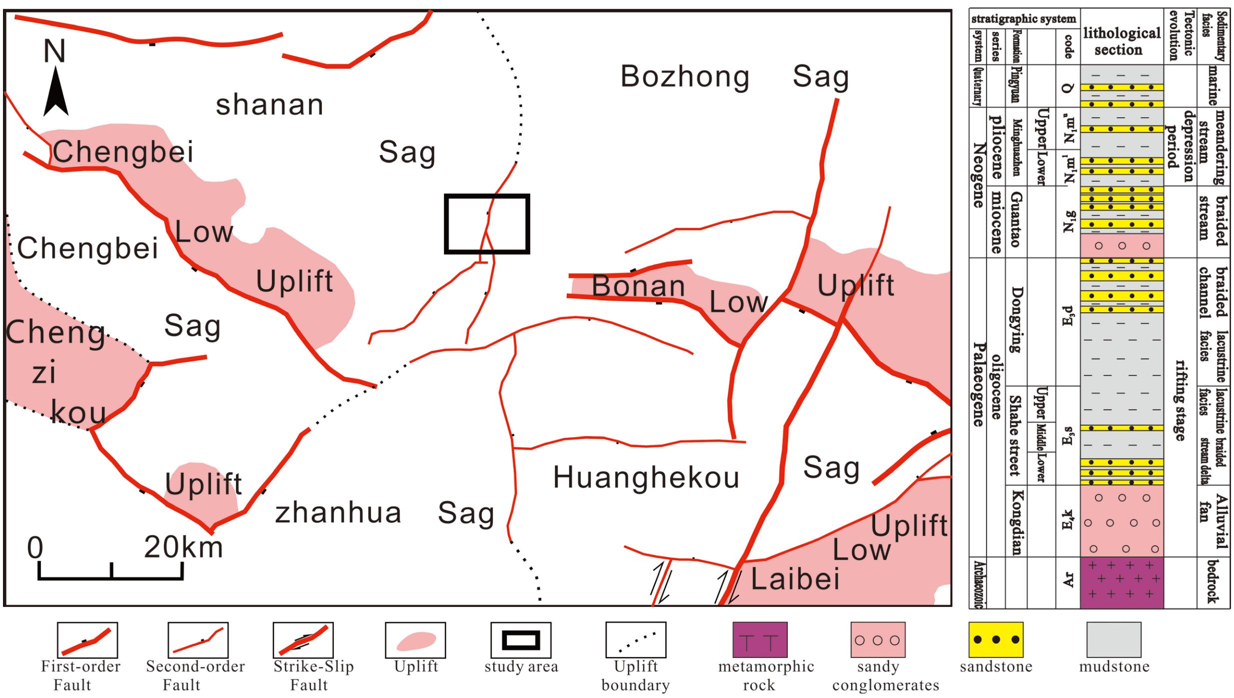
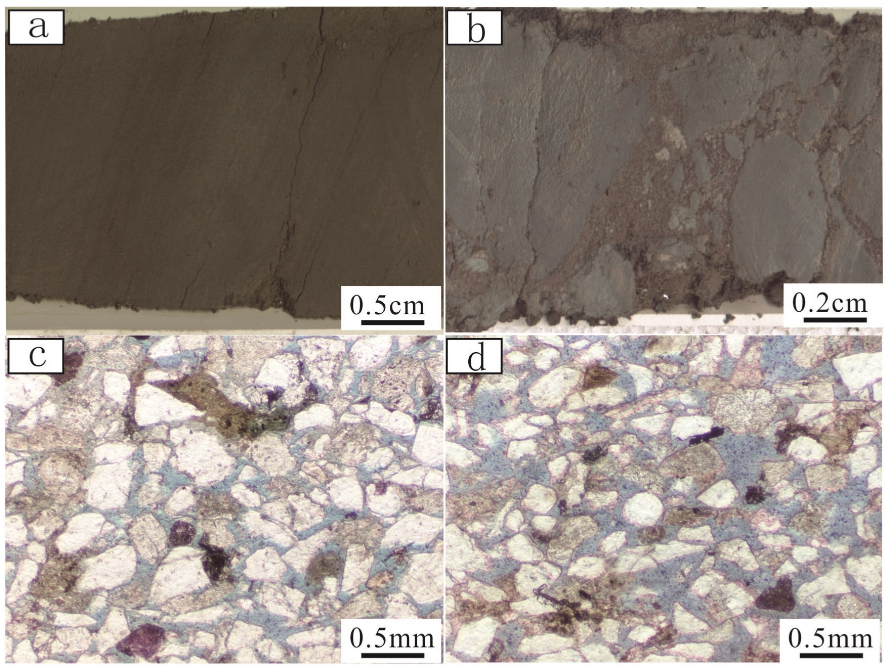


Figure 1. Regional tectonic position and stratigraphic comprehensive histogram of research region.

3. Fine Sandbody Characterization

3.1. Sedimentary Characteristics

Comprehensive analysis of core, logging, paleontological data, and sequence stratigraphy shows that during the deposition of the Lower Minghuazhen Member in the study area, the climate was warm and humid. The upper strata contain a small amount of aquatic plants locally, indicating a fluvial-dominated environment. In the lower strata, the content of algae (common in fluvial environments) decreases, diversity increases, and the content of aquatic plants rises-indicating a lacustrine-dominated environment. Overall, the sedimentary environment is shallow-water. Meanwhile, core observations, thin-section analysis, and grain size analysis reveal that the reservoir is dominated by fine sandstone and siltstone, with developed cross-bedding and parallel bedding (**Figure 2(a)**), and local mud gravels (**Figure 2(b)**). The sediments have fine grain size, high textural and compositional maturity, moderate-good sorting, subangular-subrounded grain shapes (**Figure 2(c)**), and local directional arrangement (**Figure 2(d)**). The clastic materials underwent long-distance transportation and deposition, indicating a typical shallow-water delta front environment (Hou et al., 2021).



(a) 1387.9 m, cross-bedding is developed in gray sandstone; (b) 1395m, basal lag deposits are present; (c) 1388.2 m, clastic particles show moderate to good sorting and subangular to subrounded shapes; (d) 1390.2 m, clastic particles.

Figure 2. Core sedimentation and rock-mineral characteristics of research region.

Integrating previous research results with core and logging data, the sedimentary genesis and models of the 1st and 2nd oil groups in the Lower Minghuazhen Member were determined. During the deposition of these oil groups, although the lake basin expanded further, the overall fluvial control was significant due to the shallow water in the broad basin. Sediments were transported over long distances via channels: Above the lake level, fluvial deposition dominated, with logging facies showing obvious box-shaped or bell-shaped characteristics. After entering the lake, near the shoreline, lacustrine influence was weak. Although sediments were deposited in a divergent manner overall, fluvial control remained strong (due to shallow water), leading to the development of composite channel-mouth bar deposits. Channel incision resulted in logging facies characterized by box-shaped, funnel-shaped composites, and locally funnel-shaped, with no obvious internal interbeds. As sediments prograded toward the lake center, fluvial influence weakened while lacustrine influence strengthened. Although logging facies remained composite, channel thickness decreased, and interbeds developed near the river-bar transition zone. With further progradation, sediments were dominated by composite thin-layer mouth bars and sheet sand, with logging facies showing funnel-shaped, finger-shaped, or sharp-peaked characteristics. Due to weak sediment transport toward the lake interior, distal sandbars are basically underdeveloped in the shallow lake zone; however, affected by the branching and avulsion of channels, interdistributary bay argillaceous deposits are developed between different channels. with logging facies showing finger-shaped or sharp-peaked characteristics (Figure 3).

Based on these sedimentary characteristics, the lobate shallow-water delta is divided into three zones: Channel Development Zone: Located basically above the shoreline; the focus is on describing the incised superposition relationships and internal structure of channels. River-Bar Composite Zone: Characterized by composite channel-mouth bar deposits; the focus is on describing the lateral or vertical incised superposition relationships of multi-stage lobes.

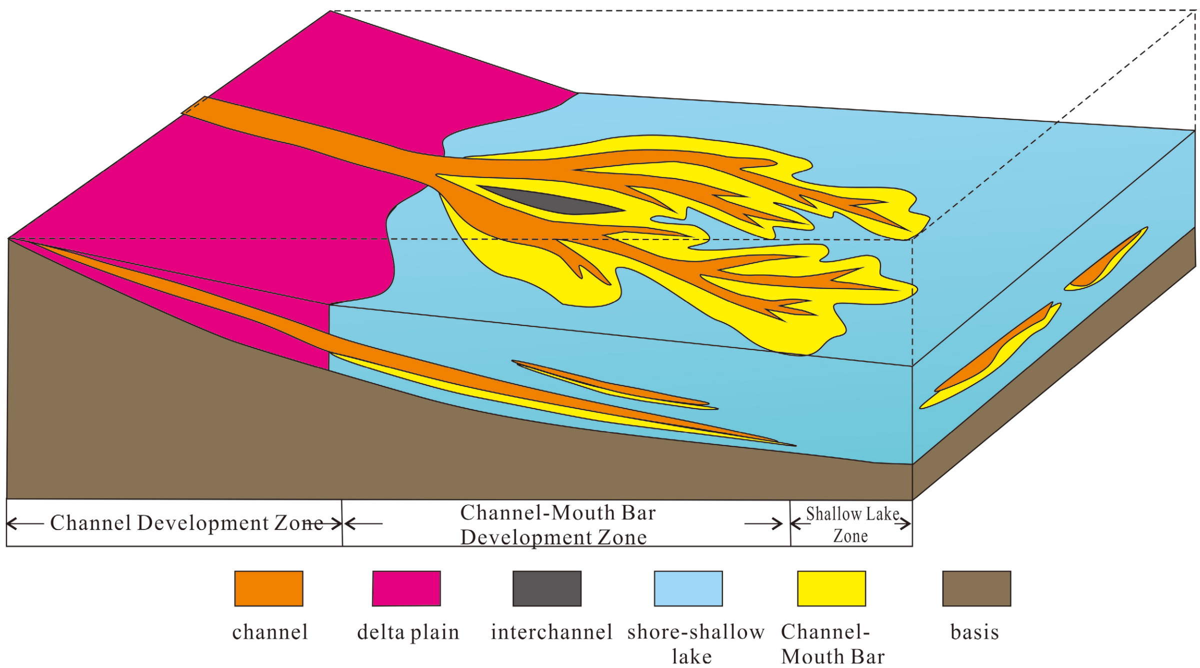


Figure 3. Sedimentary model and logging response of lobed shallow-water delta in the study area.

3.2. Characterization of Stacked Sandbody Boundaries

Based on literature research (Liu et al., 2015; Shi et al., 2015; Ji et al., 2013) and actual oilfield conditions, two types of incised superposition (lateral and vertical) and five sandbody contact patterns in the study area were summarized. Geological parameters such as sandbody width and thickness, as well as seismic parameters including the dominant frequency of the seismic wavelet and the velocity/density contrasts assumed for sand and mudstone are selected to establish a forward modeling conceptual model. The results of forward modeling experiments show that seismic waveforms are highly sensitive to changes in the contact patterns of single-channel sandbodies. With increasing incised superposition intensity of single channels, the lateral amplitude of seismic waveforms weakens, abnormal waveform characteristics become increasingly obvious, and vertical waveforms evolve from dislocation to elongation. Through seismic forward modeling, a forward response model conforming to the sedimentary mechanism of composite sandbodies in the study area was established, laying a foundation for accurately identifying the superimposition patterns and incised superposition positions of composite sandbodies.

On the basis of clarifying the seismic waveform characteristics corresponding to various sandbody contact patterns in the study area, and combined with logging facies analysis, the fine characterization of the five superimposition patterns of composite sandbodies was guided under the constraint of seismic envelope interfaces of composite sandbodies (Figure 4).

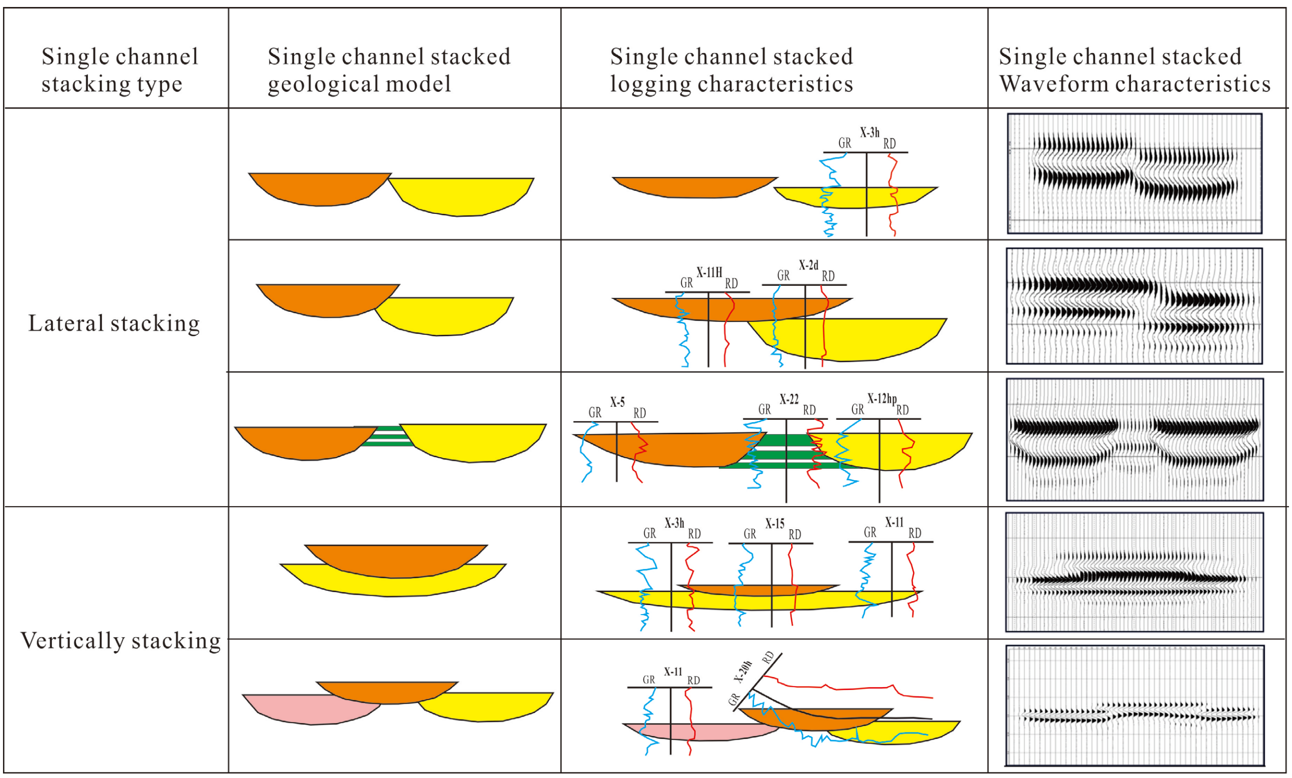
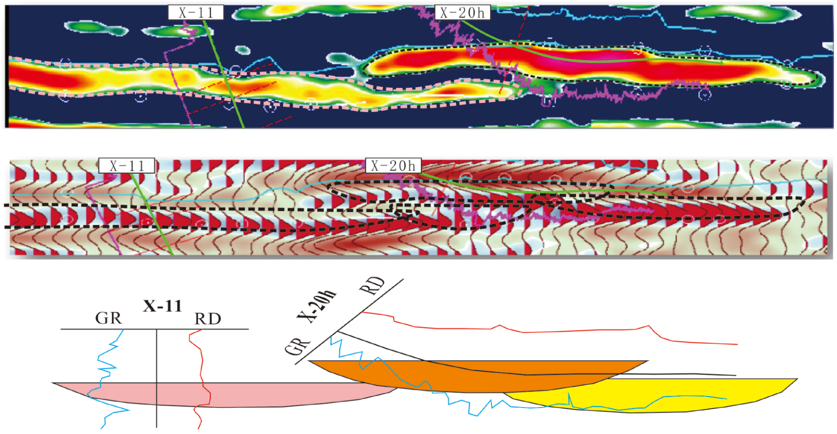


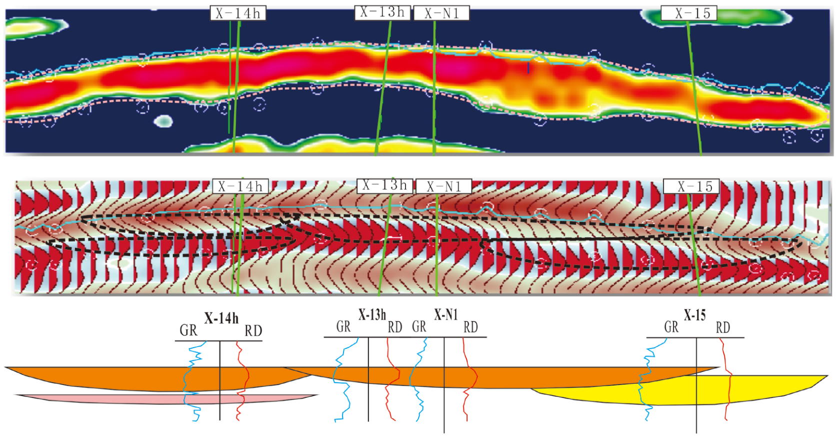
Figure 4. Identification marks for the boundary of single channel sand bodies.

- Isolated Pattern: As the sedimentary base level fell, channels prograded toward the lake basin. When encountering deposits accumulated at river mouths (which acted as barriers), the channels bifurcated and avulsed, resulting in isolated and scattered sandbodies on the plane. The actual inter-well seismic waveform characteristics are generally consistent with the forward model. By continuously revising the forward model using quantitative parameters such as the thickness of actually drilled sandbodies, sandbody distribution range, and elevation difference between two-stage sandbodies, the model was eventually consistent with the actual seismic waveform characteristics. The seismic waveform shows that the amplitude of seismic waves at the edge of channels weakens significantly, and the attitude of seismic event axes changes at the inter-sandbody mudstone deposits (**Figure 4**). The forward modeling method was used to finely characterize the inter-well sandbody contact patterns and the distribution range of two-stage sandbodies.
- Lateral Incised Contact: Channel sandbodies of this type show obvious lateral migration characteristics, with sandbody contact patterns mainly including horizontal overlapping and vertical dislocation superimposition. By comparing the actual inter-well seismic waveform characteristics of the B11~2D profile with forward modeling results, it was found that at the channel superimposition positions, the seismic wave amplitude gradually decreases and composite waveforms appear as the sandbody incision intensity increases (**Figure 4**).
- Natural Levee Connection: During the lateral migration of channel sandbodies, sedimentary hiatuses formed between two stages of channels, covered by natural levee deposits dominated by siltstone and argillaceous siltstone. The reservoir structure is often characterized by thin interbeds. The seismic waveform shows significantly weaker amplitude and larger spacing compared with the channel sandbodies on both sides, making it easy to identify.
- Vertical Accretion Superimposition: Under the sedimentary background of rapid progradation, channels migrated and avulsed frequently. Sandbodies show continuous planar distribution due to superimposition and layered vertical superposition. The seismic event axes at the sandbody superimposition positions show composite waveform characteristics.
- Composite Superimposition: Affected by both vertical superposition and lateral migration, sandbodies show multi-stage superimposition characteristics, with varying degrees of incised superposition between sandbodies of different stages. The seismic waveform at the sandbody superimposition positions shows composite characteristics with attitude changes.

Taking the N1 sandbody as an example, well-seismic integration indicates that conventional seismic profiles cannot identify the distribution characteristics of single-stage sandbodies. However, based on the waveform identification markers of different sandbody contact patterns, the vertical and planar superimposition relationships of sandbodies and sandbody boundaries can be well distinguished,

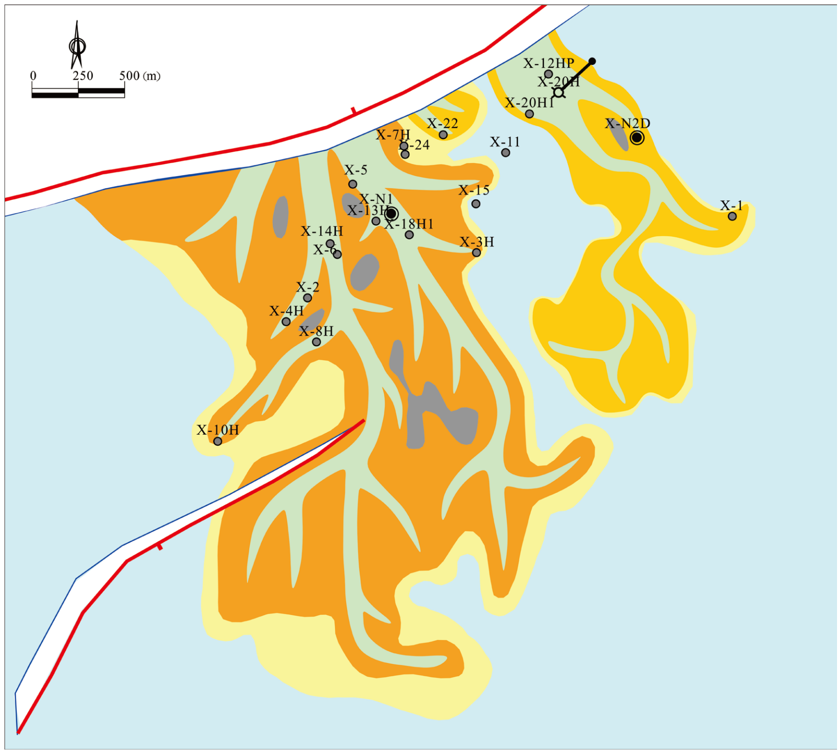


(a) Well-seismic analysis of X-11 well to X-20h well section



(b) Well-seismic analysis of X-14h well to X-15 well section

(c) Distribution of sedimentary facies in lower N1 sand



(d) Distribution of sedimentary facies in upper N1 sand

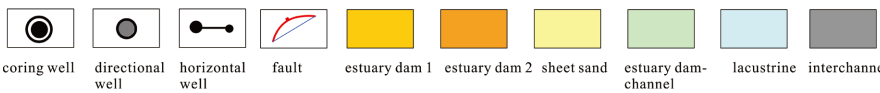


Figure 5. Single channel distribution of n1 sand in BZ oilfield.

with high well-seismic consistency (Figures 5(a)-(b)). Therefore, waveform indication was used to characterize the planar distribution of two vertical stages of sandbodies.The results show that the deposition of the N1 sandbody is mainly controlled by sediments from the northwest direction, with two vertical stages (early and late): Early-stage sandbody: Sufficient sediment supply led to the development of multiple channel-controlled lobes on the plane. Influenced by lateral migration, the lobes developed continuously and were deposited in the form of laterally incised sandbodies, with local interdistributary bay deposits between lobes (Figure 5(d)). Late-stage sandbody: Relatively weak sediment supply restricted its distribution mainly to the eastern part of the sandbody. The planar scale of the lobes varies greatly, with the main lobe located in the B20H wellblock in the east, and scattered distribution between different lobes (Figure 5(c)).

4. Remaining Oil Tapping and Practice

Combined with well-point data, understanding of sandbody superimposition patterns, and seismic attribute constraints in the study area, a refined 3D reservoir property model is established by integrating the seismic minimum amplitude attribute, sandbody connectivity probability, and sedimentary facies-controlled Kriging method, and the enrichment laws and distribution models of remaining oil were systematically summarized.

For single-channel sandbodies with low well control: Improve the production degree of low well-control areas in the same-stage channel plane by optimizing well patterns or subdividing development intervals. Horizontal wells are mainly used to expand the horizontal and vertical oil drainage area. For multi-stage superimposed sandbodies: Optimize the development well pattern for single-stage sandbodies (horizontally and vertically) or reconstruct the well pattern. Differences in horizontal and vertical waterflooding degrees are caused by vertical mudstone barriers and horizontal physical property transition zones between different channels. Horizontal wells are used to tap remaining oil in unwaterflooded areas, or directional wells are used to produce remaining oil in the top of the reservoir in specific regions. For thick superimposed sandbodies: Remaining oil is enriched in the top part. Horizontal wells are used for infill drilling to produce remaining oil in the high structural parts or the top of the reservoir between injection and production wells (Figure 6).

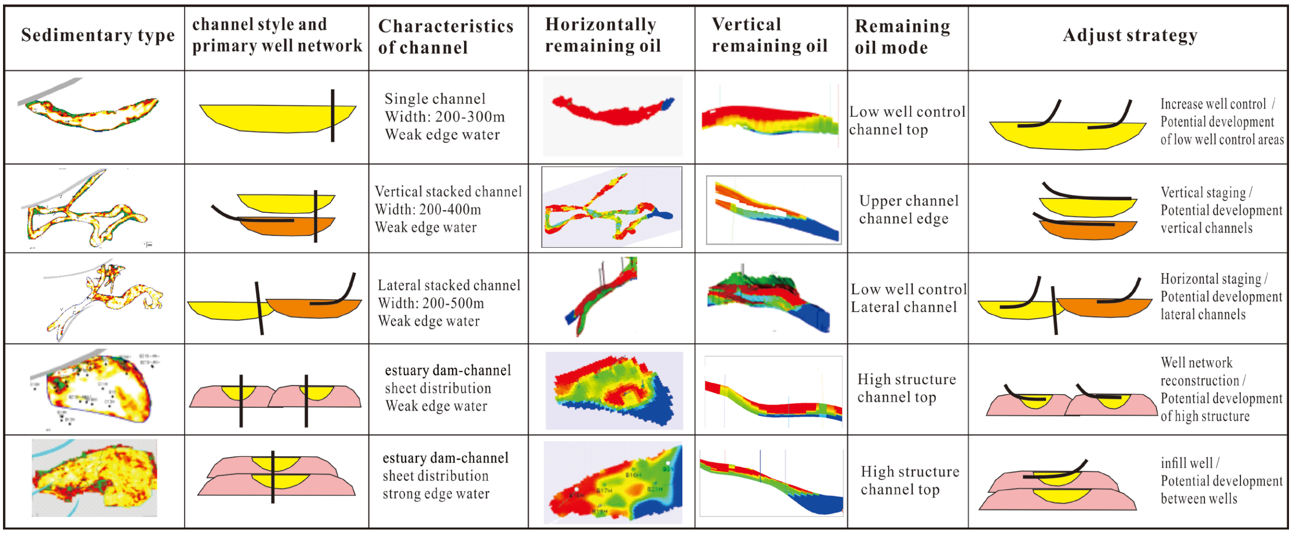


Figure 6. The relationship between the stacking style of sand bodies and the distribution of remaining oil.

The above research guided remaining oil tapping in the Lower Minghuazhen Member reservoir of the study area during the high water-cut stage. For pseudo-weak amplitude zones and sandbodies with different superimposition patterns, horizontal wells were used to subdivide development intervals and tap remaining oil-enriched areas in weak amplitude zones and areas controlled by sandbody superimposition boundaries. This effort successfully led to the drilling of 9 adjustment wells with a daily production of 100 m^3 each. The remaining 15 adjustment wells have the daily production 40~80 m^3, which meets the pre-drilling design targets. After overall infill tapping via 24 adjustment wells, the daily oil production of the study area exceeded 3,100 tons, and the oilfield recovery factor increased by 11.3%, laying a solid foundation for in-depth potential tapping in similar oilfields in the future.

5. Conclusion

1) Combined with the analysis of core, paleontological, and seismic geomorphic characteristics, the Lower Minghuazhen Member in the study area is determined to be a typical shallow-water delta front environment, with its sedimentary model gradually transitioning from a strip-shaped distributary channel type to a lobate bar type.

2) Through seismic forward modeling, seismic waveform characteristic models for different types of single-channel sandbodies were established. Five sandbody patterns (isolated, lateral incised contact, natural levee connection, vertical accretion superimposition, and composite superimposition) and their corresponding seismic response characteristics were identified, enabling the characterization of internal incised superposition boundaries of composite sandbodies.

3) Integrating the results of fine composite sandbody characterization, the enrichment laws and distribution models of remaining oil were systematically summarized. Optimizing well patterns or reconstructing well patterns for single-stage sandbodies effectively guided the implementation of adjustment wells, significantly improving oilfield development efficiency and providing guidance for later adjustment and potential tapping in similar oilfields.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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