Potential Development Study of Thin Interbedded Reservoirs Based on Detailed Reservoir Characterization and Classification Evaluation

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Abstract: ***In the early development phase of Offshore Oilfield A, the field was developed using a sparse well pattern, large well spacing, and commingled production of long intervals. Upon entering the high water-cut stage, the field faced severe interlayer interference, prominent injection-production conflicts, rapid water cut rise, and accelerated production decline. There is an urgent need to clarify the distribution patterns of remaining oil and implement late-stage development adjustments. Results: (1) Building on advances in detailed characterization of thin interbedded reservoirs in the high water-cut stage of the Penglai Oilfield, a fine characterization technology for thin interbedded reservoirs was established based on sedimentary simulation constraints. Guided by the principles of "sedimentary constraints, hierarchical dissection, well-seismic integration, and model guidance," this technology achieves precise quantitative reservoir characterization. (2) By integrating macro- and micro-scale analyses of the geological, reservoir, and development characteristics of the A Oilfield, the reservoir classification system for thin interbedded reservoirs was optimized. A quantitative interpretation technology for high-salinity water-flooded layers was developed, enabling—for the first time—quantitative evaluation of the production performance of various reservoir types in thin layered reservoirs during the high water-cut stage. (3) The target recovery factor for Type I reservoirs was determined to be 46%–50%. Although currently in the "ultra-high water cut and ultra-high recovery" stage, the recovery factor under the existing well pattern is 39%, indicating significant potential for improvement (7%–11%). Type II and III reservoirs exhibit lower current recovery degrees and hold considerable potential. (4) Based on the subdivision and recombination of layers in thin interbedded reservoirs, further research was conducted on key technologies, including optimized deployment of horizontal wells based on the genetic architecture of main sand bodies, well pattern optimization for non-main layers, and secondary infilling techniques. This established an efficient adjustment model for the high water-cut stage of thin interbedded reservoirs in the A Oilfield. Field practice shows that the successful application of this development adjustment technology system has increased the initial productivity of oil wells in the A oilfield by 3-5 times and enhanced the recovery factor by 8%～12%. This system has provided crucial technical guarantees for the safe and efficient development of Bohai oilfields during the "13th Five-Year Plan" period and offers strong technical support for their medium-to-long-term development.***

Keywords: Near-source steep slope zone; Sandy gravel bodies; Regressive fan delta; Bohai Bay Basin.

1. INTRODUCTION

For sparse well pattern development in offshore oilfields, the integrated well-seismic approach is commonly used for fine reservoir research. However, most blocks of Oilfield A suffer from low seismic resolution due to gas cloud interference, making it hard to finely describe single sandbodies and their interiors with only drilling or seismic data. As a typical large offshore thin-interbedded oilfield, Oilfield A has large vertical continuous oil-bearing intervals; restricted by engineering and cost, it adopts sparse well pattern (large well spacing) and large-interval commingled production. After entering the high water-cut stage, interlayer and planar contradictions become prominent, requiring urgent development adjustment [1-5].

Following the concept of "sedimentary constraint, hierarchical dissection, well-seismic integration, model guidance", this paper establishes a fine characterization technology for thin-interbedded reservoirs based on sedimentary simulation: it creates a sedimentary simulation method with digital geomorphic models, realizing a breakthrough from manual measurement to 3D digital analysis in experiments; integrates sedimentary simulation, dense well pattern dissection and modern river survey data to build a multi-source reservoir geological knowledge base, obtaining empirical parameters and formulas for sandbody geometry in the study area, which provides constraints for fine characterization of the fourth-order architecture of braided river sandbodies.

Furthermore, a reservoir classification system suitable for Oilfield A is established, laying a foundation for studying reservoir production status and remaining oil. Aiming at the geological characteristics and high water-cut development contradictions of large offshore fluvial oilfields, this paper summarizes key technologies (e.g., fine reservoir architecture characterization, quantitative remaining oil description) and strategies (e.g., subdivision of development layers, improvement of injection-production well pattern), providing reference for development adjustment of similar oilfields.

2. OVERVIEW OF THE STUDY AREA

Oilfield A, in the central-southern Bohai Sea, is a faulted anticline (controlled by two strike-slip fault sets) developed on the Bonan Low Uplift Belt (eastern Bohai Bay Basin) basement uplift (Figure 1).Its main oil-bearing formations are the lower Neogene Minghuazhen and Guantao Formations, with vertical continuous oil-bearing intervals (avg. 387m) including 35 small layers. It is a large offshore complex fluvial water-flooding oilfield, dominated by multi-layer sandstone thin interbeds (lithologic-structural hydrocarbon reservoir).Currently, with 83% comprehensive water cut (high water-cut stage), it faces three issues: local incomplete injection-production well pattern (low reserve production), large multi-layer commingled development (severe interlayer interference), and strong reservoir planar heterogeneity (unbalanced local injection-production). These cause rapid water cut rise, intensified decline, low recovery, and poor development.Urgent measures: well pattern infilling to boost production rate, adjusting/subdividing development layers to reduce interlayer interference, optimizing planar injection-production structure to alter underground seepage field, alleviating development contradictions.

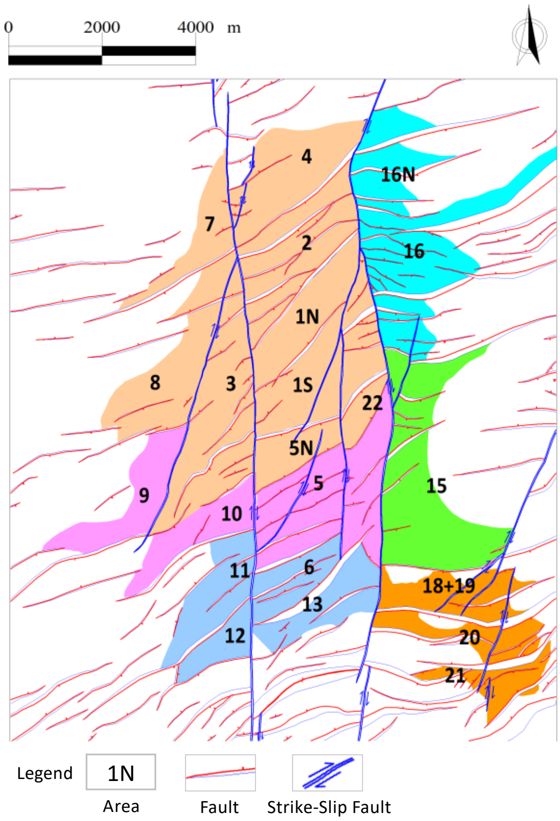


Figure 1: Tectonic Location Map of Oilfield A, Bohai Bay Basin

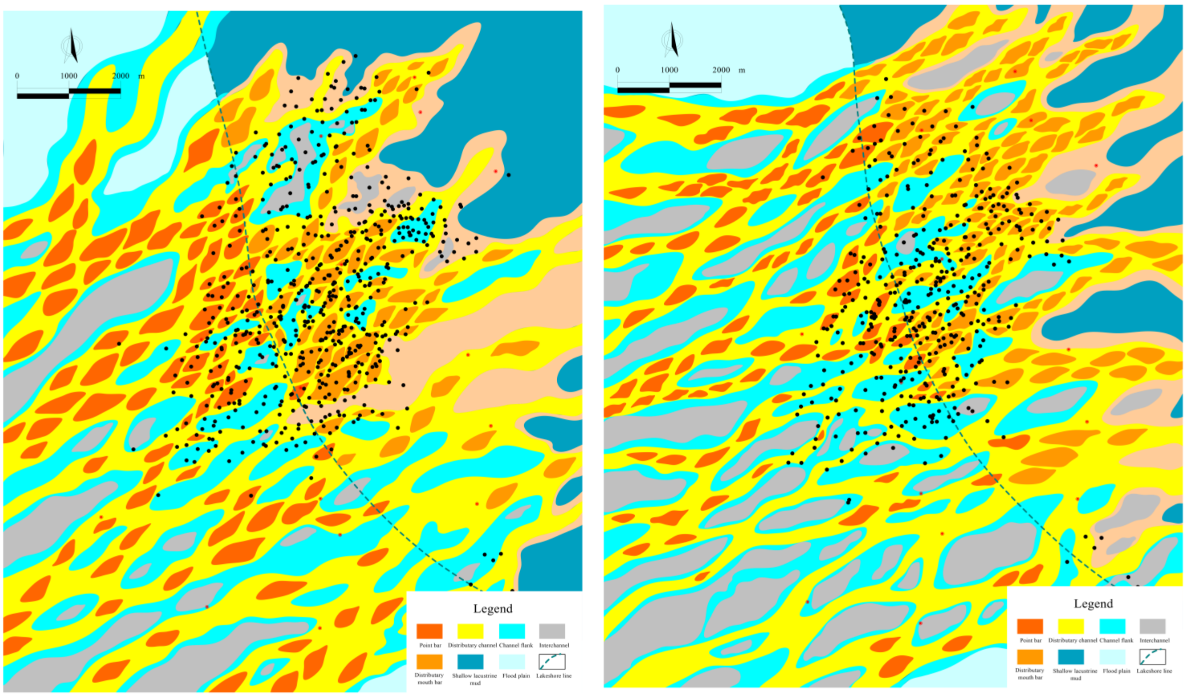
3. FINE CHARACTERIZATION OF THIN-INTERBEDDED RESERVOIRS CONSTRAINED BY SEDIMENTARY SIMULATION

The currently main producing interval in Oilfield A is the Guantao Formation, which belongs to a sandy braided river deposit. Affected by the changes in the regional main braided channel belt, the thickness of the main reservoirs varies significantly horizontally. Vertically, thin interbedded reservoirs dominated by alternating sandstone and mudstone are well-developed, with most single sand bodies ranging from 2 to 8 meters in thickness. As the main blocks gradually enter the high water cut stage, the vertical interlayer differences of thin interbedded reservoirs become increasingly prominent. There is an urgent need to carry out fine characterization of thin interbedded reservoirs to provide guidance for the study of remaining oil distribution patterns in various reservoirs and oilfield potential tapping.

For the dissection of sand body structural units with different patterns, the key lies in obtaining necessary constraint parameters to characterize their spatial distribution, and the reservoir geological knowledge base is the core constraint parameter. Traditional geological knowledge bases are mainly obtained through outcrop dissection, dense well pattern dissection, and modern sedimentary survey. There are significant differences between these methods, making it difficult to reflect the specific characteristics of the oilfield. Theoretically, the sedimentary physical simulation method can reproduce sedimentary processes and simulate sedimentary sand bodies, thereby providing new ideas and means for the quantitative construction of sand body structural parameters.

Therefore, based on the idea of "sedimentary constraint, hierarchical dissection, well-seismic integration, and pattern guidance", the "fine characterization technology of thin interbedded reservoirs based on sedimentary simulation constraints" suitable for the reservoir characteristics of Oilfield A is proposed. This technology consists of four key steps: (1) Based on the establishment of a sedimentary prototype according to the target geological characteristics of the oilfield, sedimentary simulation experiments are conducted by controlling the hydrodynamic parameters of sedimentary simulation through quantitative water and sand control equipment. A 3D scanner is used to regularly scan the sedimentary landform to obtain fine 3D topographic data and construct a three-dimensional digital elevation model (DEM), so as to realize the reproduction of sedimentary processes, quantitative analysis of sedimentary evolution processes, and clarification of the formation mechanism of sedimentary bodies; (2) Establish a integrated reservoir geological knowledge base with sedimentary simulation as the core to provide sand body structural parameters and constrain the fine characterization of reservoirs; (3) Integrate well and seismic data, and apply geological knowledge constraints. Make full use of seismic attribute analysis technology, combined with the constraints of the reservoir geological knowledge base, to guide the characterization of single sand bodies and fourth-order architectures; (4) Utilize multi-source and variable-scale thin interbedded reservoir characterization technology to accurately represent various obtained reservoir research results into the geological model, thereby improving the model conversion efficiency of reservoir research results.

Through the fine architectural dissection technology of sand bodies at different levels and based on the Petrel integrated geological research platform, the characterization of channels at different levels inside the main sand bodies in Penglai has been realized (Figure 2). This technology has changed the previous understanding that braided river reservoirs are "a monolithic block", revealing that the internal connectivity varies and differs, and has achieved fine characterization of the interior of sand bodies.



Layer L60 Layer L100

Figure 2: Sedimentary Microfacies Map of Oilfield A

4. CLASSIFICATION AND EVALUATION SYSTEM FOR THIN INTERBEDDED RESERVOIRS

With reference to the industry's reservoir classification standards and combined with the actual conditions of the oilfield, a reservoir classification standard specific to Oilfield A has been established. This standard primarily classifies reservoirs based on scores derived from reservoir thickness, sand-to-ground ratio, reservoir penetration rate, porosity, permeability, and flow coefficient. In recent years, as geological reservoir research has advanced in depth, the existing reservoir classification standard for Oilfield A has gradually shown limitations in its applicability. This study innovatively adopts a method that integrates macro and micro perspectives and combines dynamic and static data to optimize the reservoir classification system for thin interbedded reservoirs. Supported by the mercury injection experimental data of Oilfield A, the functional relationships between mercury withdrawal efficiency and parameters such as permeability, thickness, flow coefficient, porosity, and shale content were statistically analyzed and regressed. Based on the correlation, the weight coefficients of each parameter were redefined (Table 1). According to the research results, some small layers (e.g., Layer L62) have been reclassified from Type I reservoirs to Type II reservoirs due to their high shale content and poor physical properties. For other small layers, their classifications were adjusted between Type II and Type III based on factors such as shale content and physical properties. In accordance with the reservoir classification standard of Oilfield A, the reservoirs in the Guantao Formation are divided into three types. Considering the planar differences in reservoir development, reservoir classification statistics were conducted by block: Type I reservoirs: Large thickness, good physical properties and continuity, and low shale content; Type II reservoirs: Medium thickness and moderate continuity; Type III reservoirs (thickness ≤ 2m): Mostly isolated thin layers (Table 1).

Table 1: Classification and Evaluation Standards for Reservoirs in Oilfield A

Reservoir Classification	Single-layer Thickness (m)	Sand-to-ground Ratio (f)	Porosity (%)	Permeability (mD)	Variation Coefficient (f)	Shale Content (%)	Flow Coefficient (mD·m/mPa·s)
Type I	>5	>0.30	＞26	＞500	0.4～0.7	≤15	＞200
TypeII	2～5	0.2～0.3	23～28	300～500	>0.6	10～20	100～200
TypeIII	≤2	≤0.2	22～27	＜400	>0.7	10～20	＜100

In terms of sedimentary evolution, from the lower to the upper Guantao Formation, a long-term cycle of lake transgression followed by lake regression has occurred, and the north-south migration of the main braided channel belts can be observed in the planar view. A statistical analysis was conducted on 25 small layers within the L50-L100 oil groups: among them, the main braided channel belts are well-developed in 15 small layers, while they are underdeveloped in 10 small layers, which are dominated by flood deposits of different levels.

Due to the lateral migration of the main braided channel belt, the same small layer exhibits different reservoir characteristics in different blocks; therefore, there are significant differences in the reservoir classification among various blocks. Reservoirs of Type I are mostly distributed in the main braided channel belt, featuring large thickness and good lateral connectivity. Data from adjusted well water flooding and production logging tool (PLT) profiles of injection wells show that Type I layers are the main water-absorbing layers. Moreover, strong water flooding was observed in all Type I reservoirs drilled by adjustment wells, which verifies the good connectivity of Type I reservoirs and the reliability of the relevant geological understanding. By using reprocessed seismic data and combining well logging with seismic data, Type I reservoirs can be identified within the resolution range of seismic data. Among them, reservoir sand description research can be carried out for the upper member of the Guantao Formation. Based on the results of sand description, 12 horizontal wells have been drilled in the Guantao Formation in Blocks 1/3/8/9, with an average sandstone encounter rate of 92%, which further confirms the high reliability of the geological understanding of Type I reservoirs. Reservoirs of Type II and III are developed in the braided river delta front or flood plain facies, with relatively thin thickness and moderate to poor connectivity. Through fine drilling correlation and the combination of dynamic and static data, it is considered that the thickness of Type II reservoirs is generally 2-5 meters. Data such as water flooding indicate that the current well pattern can effectively produce from these reservoirs. Combined with the sedimentary and reservoir development models, Type II reservoirs are developed at the edge of the main Type I reservoir layers, with an aspect ratio (width to thickness) of 50-70:1. Their distribution direction is consistent with that of Type I reservoirs, showing a northeast-southwest trend. Type III reservoirs are mainly developed in overbank microfacies during flood periods, delta front sheet sand microfacies, and small channels formed during flood periods. They are mostly potato-shaped, with an aspect ratio (length to width) of 1.5-3:1 and a width of 50-200 meters, and have poor directional continuity. With a thickness of less than 2 meters, it is difficult for these reservoirs to achieve effective injection and production responses.

5. RESEARCH ON DEVELOPMENT ADJUSTMENT STRATEGIES

After entering the high water-cut stage, Oilfield A implemented comprehensive adjustments to its main production areas. The strategy aimed to maximize the potential of existing facilities and well patterns by implementing targeted technical measures such as gradually subdividing development horizons, optimizing injection-production well patterns, enhancing recovery methods, and converting well types. These adjustments were applied vertically, horizontally, and within individual layers to improve overall development performance and increase recoverable reserves. This process resulted in the establishment of a mature set of development adjustment strategies for large offshore fluvial-dominated oilfields in the high water-cut stage. These strategies provide a valuable reference model for future development adjustments in the Bohai Oilfield and offer a framework of ideas and methods for similar oilfield development projects.

5.1 Classified Evaluation of Reservoir Production Performance and Remaining Oil Distribution Patterns

Based on the refined time-varying numerical simulation, it is clarified that there are significant differences in the production performance of various types of reservoirs. The average recovery factor of the produced reserves in the Guantao Formation of the main blocks is 21.6%. The production status varies greatly among different reservoir types: the recovery factor of Type I reservoirs is 30.9% with a comprehensive water cut of 92%; the recovery factors of Type II and Type III reservoirs are 13.5% and 4.8% respectively, and their comprehensive water cuts are 65% and 15% respectively. For Type I reservoirs, based on empirical formulas and benchmarking with Suizhong 36-1 Oilfield, the target recovery factor is predicted to be 46%-50%. Although Type I reservoirs have entered the "double extra-high" stage (extra-high water cut and extra-high recovery degree), the current well pattern recovery factor is 39%, leaving a large room for improvement (7%-11%). Type II and Type III reservoirs currently have relatively low recovery factors and thus hold great potential. Based on the refined characterization of thin-interbedded reservoirs, technologies such as water flooding analysis of multiple rounds of side-track wells, reservoir engineering methods, and numerical simulation methods were used to study the distribution law of remaining oil. This research systematically summarized the vertical, planar, and intra-layer remaining oil distribution patterns and their main controlling factors in offshore thin-interbedded reservoirs during the high-water-cut stage. On the basis of improving the reservoir classification system of Oilfield A by integrating macro and micro sedimentary facies, the significant differences in the production performance of various reservoirs were identified through the implementation of quantitative interpretation of high-salinity water-flooded layers, improvement of remaining oil description via reservoir engineering methods, and development of refined numerical simulation for permeability time variation and PI (Productivity Index) pattern fitting. Consequently, different development strategies should be adopted for different reservoir types. Although Type I reservoirs have entered the "double extra-high" stage, water flooding is mainly concentrated in the lower part, while the upper part is enriched with remaining oil. Based on the remaining reserves and target recovery factor, the following conclusions were confirmed: Type I reservoirs have a large reserve base and significant room for further improvement in recovery factor, so they remain the main target for potential tapping at the current stage; Type II reservoirs currently have relatively low recovery factors and water cuts, showing great potential. This achievement has realized, for the first time, the quantitative evaluation of the production effectiveness of various reservoirs in high-water-cut thin-interbedded reservoirs like those in Oilfield A.

5.2 Research on Well Pattern Adaptability

The reservoirs in the lower member of the Minghuazhen Formation in Oilfield A are dominated by meandering river deposits, with sandbodies mostly distributed in a banded or potato-like shape. The Guantao Formation is mainly characterized by braided river deposits, where sandbodies are mostly distributed as extensive connected bodies.

Combined with the research results on the distribution law of single sandbodies, an irregular well pattern is adopted for development in areas of the Minghuazhen Formation reservoirs where the local vertical superimposition relationship is good, there is a certain distribution range, and an effective injection-production well pattern can be formed. For the large-scale integral blocks in the Guantao Formation, the early development was mainly based on the inverted nine-spot well pattern. Considering the current water cut and formation pressure changes, the well pattern has been adjusted to a line-drive injection-production well pattern to enhance water injection. The traditional pattern of separating development by reservoir intervals was broken, and a three-dimensional adjustment model based on classified reservoir development was established, which is a three-dimensional adjustment model combining horizontal wells for main reservoirs and directional wells for non-main reservoirs for commingled production (Figure 3). Through the analysis of water cut contour maps, it is found that the current well spacing of 250-300 meters can effectively control the main reservoirs. Combined with the research on the adaptability of well pattern and well spacing in reservoir engineering [27-28], the reasonable well spacing in the study area is determined to be 250-300 meters. A study on the well pattern adaptability of complex fluvial oilfields shows that the line-drive injection-production well pattern is superior to the five-spot injection-production well pattern and the staggered line-drive injection-production well pattern. In the five-spot and staggered line-drive injection-production well patterns, some oil wells are distributed on the main flow lines, resulting in relatively high initial water cut of these oil wells. Additionally, both well patterns have a large number of injection wells and a small number of production wells, leading to a rapid overall water cut rise. Therefore, the development effect of the line-drive injection-production well pattern is significantly better than that of the other two.

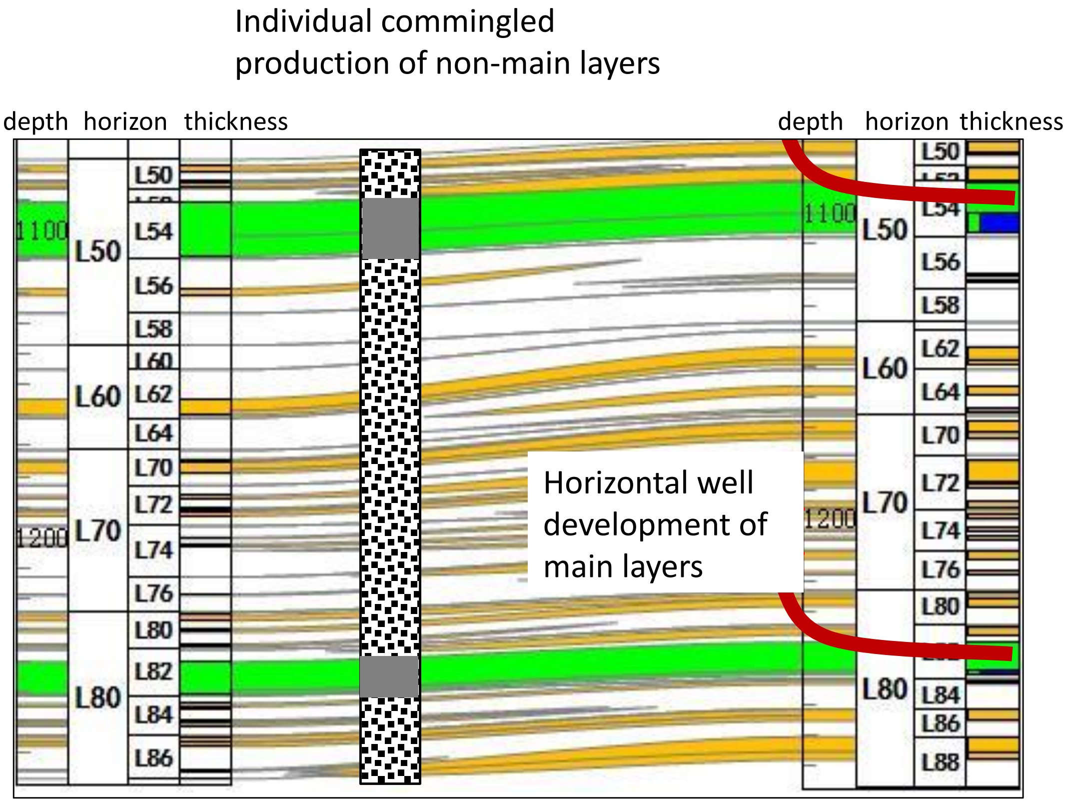


Figure 3: Schematic diagram of the three-dimensional adjustment model combining horizontal wells in main layers with directional wells in non-main layers for commingled production

5.3 Fine-scale Potential Tapping of Remaining Oil Using Horizontal Wells

Oilfield A features a relatively large vertical stacked thickness, predominantly composed of thin interbedded layers, with directional wells as the primary well type. Based on remaining reserves and recovery efficiency, it is clear that: Type I reservoirs remain the primary target for potential tapping at this stage Long-term water injection has led to severe water flooding at the bottom of pay zones during the high water-cut stage Remaining oil tends to accumulate in the middle-upper sections of the reservoir. Horizontal wells can be effectively used to tap this type of remaining oil In the lower section of the Ming Formation, reservoirs are primarily strip-shaped or potato-shaped. Some single sand bodies cannot be effectively drained by directional wells, so horizontal wells can be deployed within larger single sand bodies to improve degree of reserve utilization.

Combining fine-scale reservoir architecture characterization with quantitative remaining oil description, reservoir numerical simulation and comprehensive dynamic analysis were used to determine the horizontal well deployment criteria: pay thickness greater than 8 m, well-controlled reserves exceeding 400,000 m^3, vertical distance from water-flooded zones more than 5 m, and horizontal distance from directional wells of 120 m.

6. PRACTICAL EFFECTS

Based on the geological reservoir characteristics and remaining oil distribution pattern of Oilfield A, the following development adjustment strategies were implemented in Blocks 1/3/8/9: (1) The Minghuazhen Formation (with crude oil viscosity of 167-262.8 mPa·s) and the Guantao Formation (with crude oil viscosity of 9-20 mPa·s), both having relatively high formation crude oil viscosity, were separated. Meanwhile, the Guantao Formation, which contains a large number of oil layers (35 small layers), was subdivided into the Upper Guantao Formation (oil groups L50-L70) and the Lower Guantao Formation (oil groups L80-L120). The development method was adjusted from commingled production of one development interval system to separate production of three development interval systems; (2) The injection-production well pattern was adjusted from the inverted nine-spot well pattern to the line-drive well pattern, with the injection-production well spacing basically maintained at 250-300 meters. The research on the ODP (Overall Development Plan) for the development adjustment of Blocks 1/3/8/9 in Oilfield A was completed in 2014. From 2014 to 2016, the adjustment was implemented in advance using empty well slots and low-efficiency wells, with a total of 30 adjustment wells drilled. The initial average daily oil production per well was 118-141 m^3/d, which was 70-80% higher than that of the surrounding old wells. The water cut of the new wells was 24-56%, far lower than that of the surrounding old wells. It can be seen from the relationship curve between water cut and recovery factor that the oilfield development effect has improved.

7. CONCLUSIONS

1) Combined with the progress in the fine characterization of thin-interbedded reservoirs in the high-water-cut stage of the Penglai Oilfield, and in accordance with the concept of "sedimentary constraint, hierarchical dissection, well-seismic integration, and pattern guidance", a fine characterization technology for thin-interbedded reservoirs based on sedimentary simulation constraints was established, realizing the fine quantitative characterization of reservoirs.

2) According to the actual geological reservoir and development characteristics of Oilfield A, the quantitative evaluation of the production effectiveness of various reservoirs in high-water-cut thin-interbedded reservoirs like those in Oilfield A was achieved for the first time.

3) It was clarified that the target recovery factor of Type I reservoirs is 46%-50%. Although Type I reservoirs have entered the "double extra-high" stage, the current well pattern recovery factor is 39%, leaving a large room for improvement (7%-11%). Type II and Type III reservoirs currently have relatively low recovery factors and thus hold great potential.

4) On the basis of the division and reorganization of intervals in thin-interbedded reservoirs, further research was conducted on key technologies such as horizontal well optimization and deployment technology based on the genetic structure of main sandbodies, well pattern optimization and secondary infill technology for non-main reservoirs. For the first time, an efficient adjustment model for thin-interbedded reservoirs in Oilfield A during the high-water-cut stage was established.

In response to the development characteristics of large offshore complex fluvial oilfields—such as intricate reservoir conditions, a high proportion of heavy oil reserves, and limited testing data—technological breakthroughs were achieved through focused research. Key challenges were overcome in conducting fine-scale reservoir characterization and quantitative remaining oil description under poor seismic data quality conditions for large complex fluvial reservoirs. Through production practice, an efficient development adjustment strategy was established that targets remaining oil through detailed measures such as: Subdividing development horizons Optimizing injection-production well patterns Implementing appropriate well type adjustments This process also resulted in the formation of a comprehensive technical system for development adjustments during the high water-cut stage in large offshore complex fluvial oilfields. This system has become a core technology supporting the sustainable development of the Bohai Oilfield, successfully guiding development adjustment studies in multiple blocks of the Penglai Oilfield Group and similar fields, and providing strong technical assurance for achieving the "13th Five-Year Plan" production targets.

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