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# Study on the Distribution of Interlayer in Thick Sandy Braided River under Large Well Spacing

## —A Case of C Oilfield in Bohai Sea

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## Abstract

Using core, logging and other data, combined with field outcrop deposition, this paper studies the sedimentary genetic types and sedimentary stages of thick sandy braided river interlayer in C oilfield, and divides two stages of interlayer and three single-stage braided flow zones. On this basis, geostatistical inversion constrained by logging and discerning River quantitative knowledge base is carried out to predict the distribution range of the main interlayer in the two phases. The production performance test of the blind well and horizontal well shows that the coincidence rate of the prediction results of interlayer with thickness > 1.5 m is 75%. The research shows that the first stage is the main interlayer, mainly composed of mudstone of flood plain origin, with an average thickness of 2.1 m and relatively stable distribution. Based on the interlayer prediction results, the small layer of composite sand body 1 forms a residual oil enrichment area in the high part of the structure due to the wide range of interlayer shielding in the lower part, which is a favorable area for adjusting and tapping potential.

## Keywords

Bohai Oilfield, Braided River, Horizontal Well, Geostatistical Inversion, Interlayer Prediction

## 1. Research Background

A thick sandy braided river is an important sedimentary type and oil and gas producing layer in the Bohai oilfield. Most of the reservoir types are massive bottom water reservoirs, in which the relatively stable distribution of argillaceous interlayer is the key geological factor affecting the development effect. A large number of development practices show that interlayer plays an important role in controlling the production performance and remaining oil distribution of bottom water reservoir [1] [2] [3] [4] [5]. Therefore, it is very important to deeply carry out the description and prediction of the interlayer distribution of thick braided river for understanding, adjusting and tapping the potential of remaining oil distribution of bottom water reservoir in high water cut stage.

At present, many scholars have carried out detailed research on interlayer lithology, sedimentary genetic type, sedimentary model and geometric shape of different levels in sandy braided rivers according to core, logging and field outcrop data. At the same time, dense good patterns and three-dimensional seismic data are used to finely characterize and characterize interlayers between wells [6]-[13]. However, in view of the high investment and high risk of offshore oilfield development, sparse well pattern and lack of core data, the interlayer prediction method under the control of dense well pattern in onshore oilfields is difficult to be copied to offshore oilfields. In addition, due to the cutting and superposition of multi-stage channel sand bodies in thick braided river sediments, the interlayer is usually unstable, and the thickness and distribution scale are generally small. It is difficult to characterize the spatial distribution of interlayers by conventional seismic means.

The C oilfield in the Western Bohai Sea is such a typical example. The main development layer of the oilfield is the lower member of the Guantao Formation III oil formation (hereinafter referred to as NgIII down), which develops extremely thick sandy braided river deposits. The drilling reveals that the thickness of the reservoir is 350 - 400 m, and the oil-gas bearing interval is located at 15 - 25 m at the top of the reservoir. The reservoir type is a massive bottom water reservoir with a gas cap, which is developed with irregular horizontal well pattern of natural energy. At present, it includes 12 exploration wells and crossing wells, 35 horizontal production wells, and the length of horizontal section is 200 - 400 m.

At present, after more than ten years of development, NgIII has a high degree of recovery and has entered the stage of ultra-high water cut, with a comprehensive water cut of 95%. Due to the frequent changes in sedimentary base level and hydrodynamic force, multi-stage braided river channels are cut and superimposed and mud, physical interlayer and mud gravel interlayer at all levels are randomly developed, which makes the internal structure of the reservoir extremely complex and restricts the understanding, adjustment and potential tapping of remaining oil.

## 2. Genetic Type and Sedimentary Period of Interlayer

### 2.1. Lithology and Genetic Type of Interlayer

#### 2.1.1. Interlayer Lithology

According to the data of two coring wells in the study area (**Figure 1**), the lithology of the interlayer is mainly green gray mudstone, argillaceous silt interlayer, calcareous cemented argillaceous siltstone interlayer, argillaceous gravel interlayer and silty fine sandstone physical interlayer. It is mainly of massive

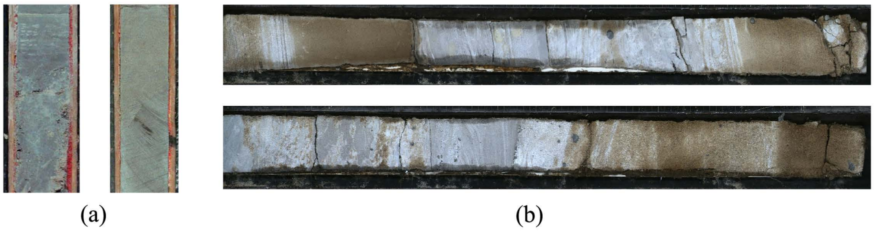

**Figure 1.** Lithologic characteristics of interlayer of the NgIII down formation. (a) Light green calcareous interlayer; (b) Grey white argillaceous interlayer.

structure, with few horizontal bedding. The thickness of local interlayer is relatively thick, about 0.4 - 0.7 m.

### 2.1.2. Genetic Type of Interlayer Sedimentation

The study area is mainly the interlayer formed by sedimentation, and the calcareous interlayer caused by diagenesis is less distributed. By investigating and comparing the development characteristics of interlayer in the outcrop section of sandy braided river under similar sedimentary background [6] [10], combined with the characteristics of lithology and logging facies of interlayer in the study area, it is considered that the interlayer under NgIII can be mainly divided into five different sedimentary genetic types, namely flood plain mudstone, abandoned/end-stage channel argillaceous filling (or semi filling) Mud between dams, mud and gravel deposits in riverbed and muddy or silty deposition layer in core beach dam. According to the sedimentary characteristics of interlayer and well correlation (**Figure 2**), interlayer is mainly caused by flood plain mudstone, abandoned River argillaceous filling (or semi filling) and inter dam argillaceous interlayer, which has a certain distribution range and comparability. It is the main interlayer type of the oilfield.

## 2.2. Interlayer Logging Identification

According to the lithologic, physical and electrical characteristics of the interlayer under Ng III down, the interlayer can be divided into two types, namely argillaceous and physical interlayer. Through the analysis of the logging response characteristics of the interlayer, the logging identification standard of the interlayer is established by using the intersection diagram method (**Table 1**). The logging response characteristics of the muddy interlayer are: high gamma, high density and low resistivity. The response characteristics of physical interlayer are: low gamma, high density and low resistivity. It is distinguished from argillaceous interlayer by relatively low gamma value and high density.

## 2.3. Period Division of Interlayer

According to the principle of approximate equal elevation and equal thickness comparison of fluvial facies, according to the distribution characteristics and development needs of interlayer, the top oil-bearing interval of NgIII down formation is subdivided into three single stage braided flow zones, corresponding

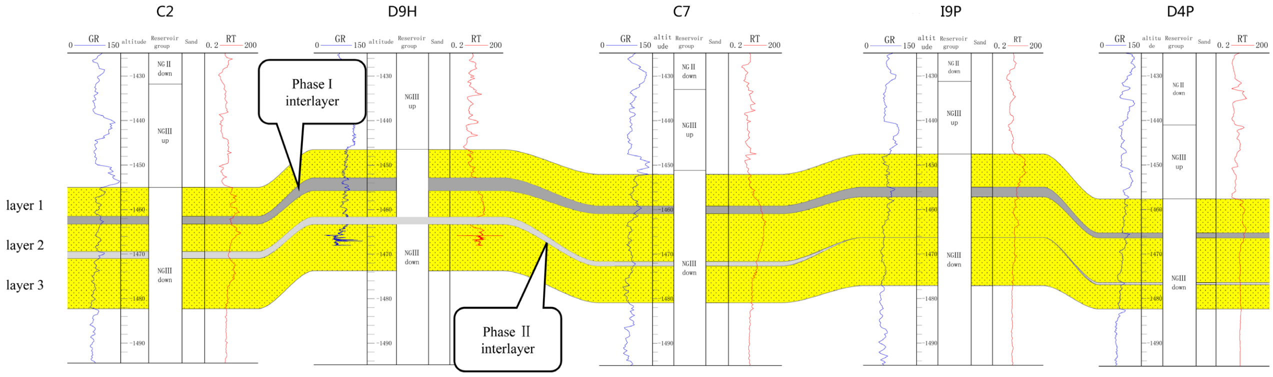

**Figure 2.** Main sedimentary origin types and correlation sections of interlayer in NgIII down formation.

**Table 1.** Identification standard table of interlayer of the NgIII down formation.

| Type | GR | DEN | RT |
|---|---|---|---|
| | API | g/cm$^3$ | Ω·m |
| Sandstone | 50 - 82 | 2 - 2.25 | 2.5 - 25 |
| Muddy interlayer | >80 | 2.2 - 2.35 | <7 |
| Physical interlayer | 75 - 100 | 2.2 - 2.5 | 3 - 8 |

to three small layers respectively. Two stages of relatively stable interlayer are developed between the small layers (Figure 2). Among them, the interlayer in the first stage is mainly filled with flood plain mud and abandoned river mud, with relatively stable distribution. The thickness above the well is 1.0 - 4.2 m, with an average of 2.1 m. There are various genetic types of interlayer in phase 2, including flood plain mud, inter dam mud, ditch mud filling and scouring mud gravel at the bottom of the river channel. Due to the frequent change of river channel scouring and hydrodynamic force, the thickness is thin and changes rapidly laterally, with poor contrast. The thickness above the well is 0.5 - 2 m, with an average of 1.2 m.

## 3. Interlayer Prediction Based on Geostatistical Inversion

The main frequency of seismic data of NgIII down lower oil formation is 35 Hz, the interval velocity is about 2200 m/s, and the data resolution is about 15 m, while the interlayer thickness is generally less than 4 m, so it is difficult to accurately describe the interlayer distribution by conventional attributes and inversion methods. Therefore, geostatistical inversion method is introduced. It is a technology integrating geostatistical modeling and deterministic inversion. It mainly uses variation function to describe and evaluate the structural and scale changes of geological characteristics in vertical and horizontal directions. It can fully integrate the advantages of vertical resolution of geology and logging and horizontal resolution of earthquake. Combined with Markov Chain Monte Carlo (MCMC) simulation algorithm, lithofacies bodies and lithofacies probability bodies with a series of constraints [14] [15] [16] [17] [18], so as to improve the resolution of seismic data and predict the spatial distribution of thin interlayer.

According to the geological, seismic and petrophysical characteristics of interlayer in the two phases of NgIII down lower oil formation, the geostatistical inversion method guided by logging constraints and geological knowledge base is used to carry out thin interlayer prediction. The specific research ideas are as follows: 1) Improving the resolution of interlayer prediction by introducing the high-frequency information of logging, especially the data of multiple horizontal wells; 2) Through the geological knowledge base of sandy braided river sedimentation, the low-frequency trend guides the optimization of variation parameters and improves the rationality of trend simulation; 3) Finally, the rationality and accuracy of quality control prediction results are verified by blind well error and reservoir performance of production wells.

### 3.1. Petrophysical Characteristics

Based on the classification of rock elastic attribute and logging lithology, the elastic attribute sensitive to lithology is expressed. Its purpose is to study the corresponding relationship between elastic attribute and lithology by using the elastic parameters of logging. Considering that there are certain differences in the petrophysical characteristics of each small layer, the statistical analysis of petrophysical parameters by small layers can effectively eliminate the "illusion" of P-wave impedance superposition caused by differential compaction. Figure 3 shows the statistical histogram of multi well P-wave impedance and lithology divided by sub layers. It can be seen that the P-wave impedance of each sub layer has a good distinction between sand and mudstone, sandstone has low impedance and mudstone has high impedance, which lays a petrophysical foundation for seismic inversion.

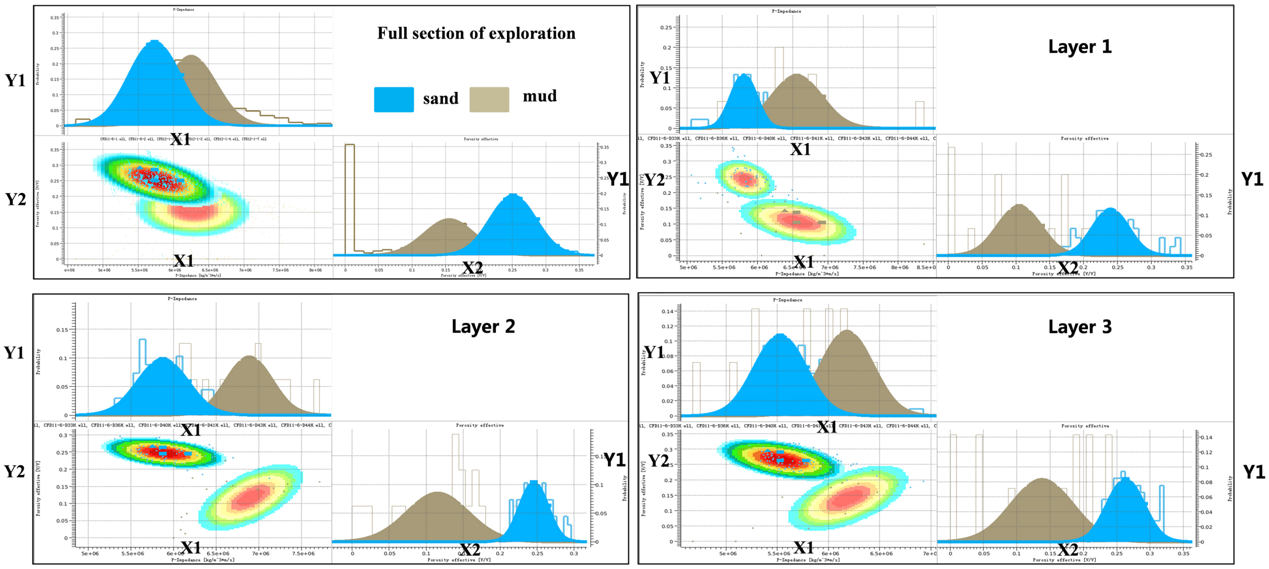

Figure 3. Statistical histogram of impedance and lithology of each layer of NgIII down formation. X1-longitudinal wave impedance; X2-effective porosity; Y1-frequency distribution; Y2 effective porosity.

### 3.2. Variogram Analysis

The optimization of vertical variation function in traditional geostatistics inversion mainly depends on well data statistics, and the horizontal variation function mainly comes from dense well pattern. In this study, the longitudinal variation range of variation function mainly depends on well data and prediction demand, and the transverse variation function mainly comes from deterministic inversion and quantitative knowledge base of sandy braided river deposition.

Predecessors [6] [8] [10] [15] summarized the geological knowledge base such as the geometric shape, vertical and horizontal distribution range of sandy braided river interlayer by using the methods of dense well pattern anatomy and field outcrop actual measurement. Combined with the actual geological characteristics of the study area, they summarized the geological knowledge base of different genetic reservoirs and interlayer of NgIII down lower oil formation (**Table 2**) as the constraint conditions of variation function.

According to the above well statistical analysis, the sedimentary microfacies of each small reservoir of NgIII down lower oil formation are mainly bar, and the thickness of a single stage is 6 - 7 m. According to the empirical formula of sedimentary configuration unit scale of sandy braided river summarized by predecessors, it is calculated that the single core beach dam is 200 - 260 m wide, 900 - 1100 m long and the length width ratio is 3.5 - 5.2. Comprehensively considering the distribution characteristics and scale of reservoir and interlayer, it is finally determined that the longitudinal variation range of reservoir of the first layer in NgIII down is 2 ms, the main variation range is 400 m and the secondary variation range is 1200 m. The vertical range of the Phase I interlayer is 1 ms, the main range is 1200 m and the secondary range is 2300 m (**Figure 4**). Finally, this method is used to determine the variable range parameters in all directions of the reservoir and interlayer of all the layers, providing constraints for statistical inversion.

### 3.3. Inversion Results and Verification

Based on the optimization of variation function, the sequential Gaussian random simulation method is used to simulate the reservoir parameters, integrate the logging data and deterministic inversion, establish a high-resolution reservoir model, and obtain the lithofacies probability volume through comprehensive operation.

Through deterministic inversion and 90 degree phase shift trend comparison, the rationality of geostatistical inversion results is analyzed. **Figure 5** shows the original seismic, 90 degree phase shift and geostatistical lithologic probability body profile passing through well C1. It can be seen that the statistical inversion has the same description of the overall reservoir structure, and the vertical resolution is higher than 90 degree phase shift, which has a fine description of the discontinuous thin interlayer.

In order to analyze the quality control of the prediction results, the statistical analysis of the error of blind wells not involved in the inversion operation (**Figure 6**)

Table 2. Geological knowledge base of different origin interlayer of the NgIII down oil formation.

| type | Sedimentary genetic type | Thickness (m) | Width (m) | Length-width ratio |
|---|---|---|---|---|
| Class I | Flood mudstone | 1 - 4, average 2.1 | 300 - 800 | 1.8 - 3.2:1 |
| Class II | Abandoned river course and mud between dams | 0.5 - 2.1, average 1.1 | <300 | 2.5 - 4.2:1 |
| Class III | Muddy channel/silt layer | 0.1 - 0.6, average 0.3 | <100 | - |

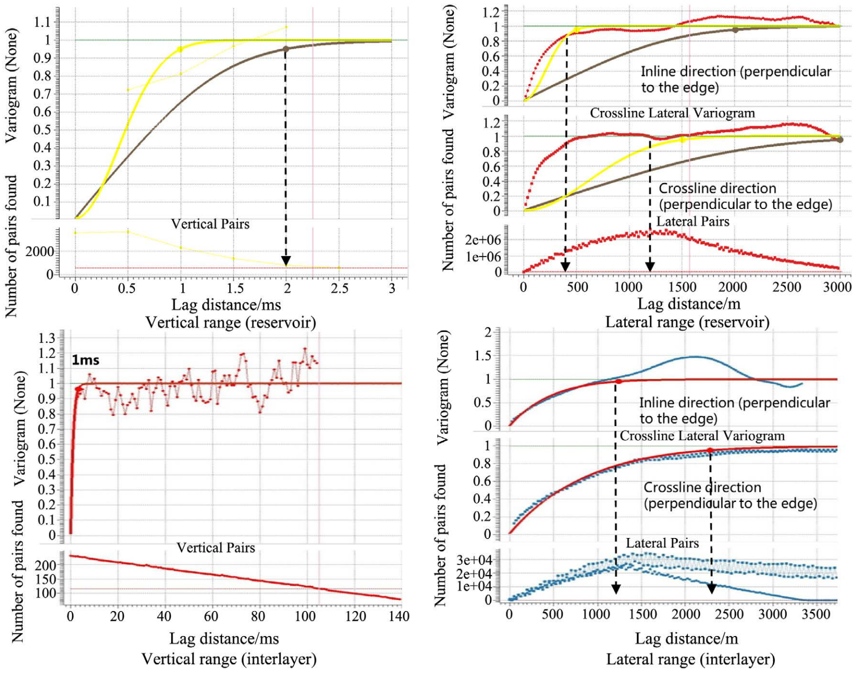

Figure 4. Optimization of variation function of reservoir and mudstone in the first layer of the NgIII down.

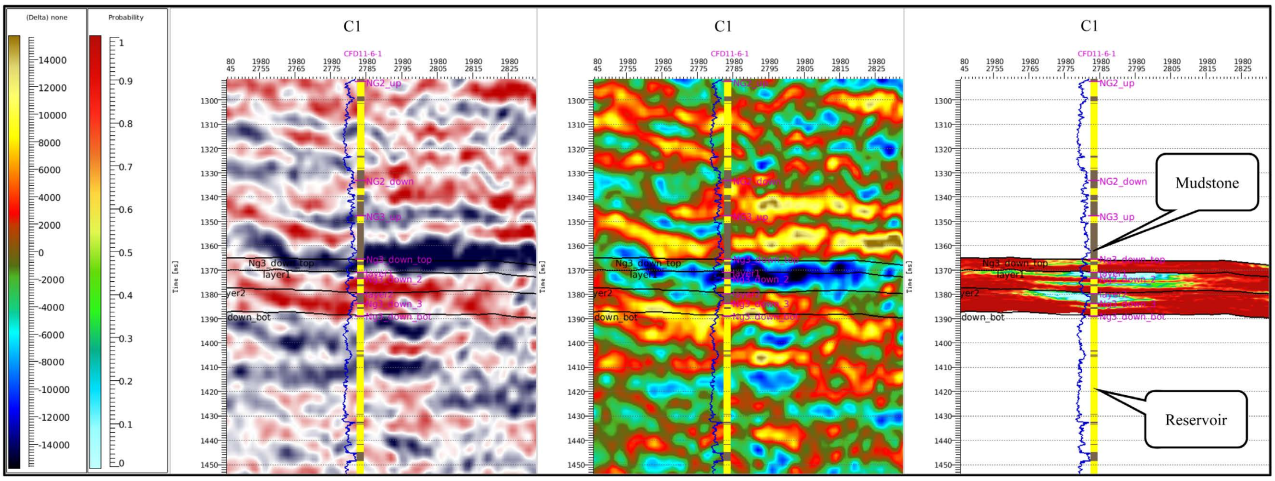

Figure 5. Comparison of original seismic, 90˚ phase-shift and geostatistical lithologic probability volume sections through well C1 of the NgIII down Formation. (a) seismic profile; (b) 90 degree phase shift profile; (c) geostatistical lithologic probability volume profile.

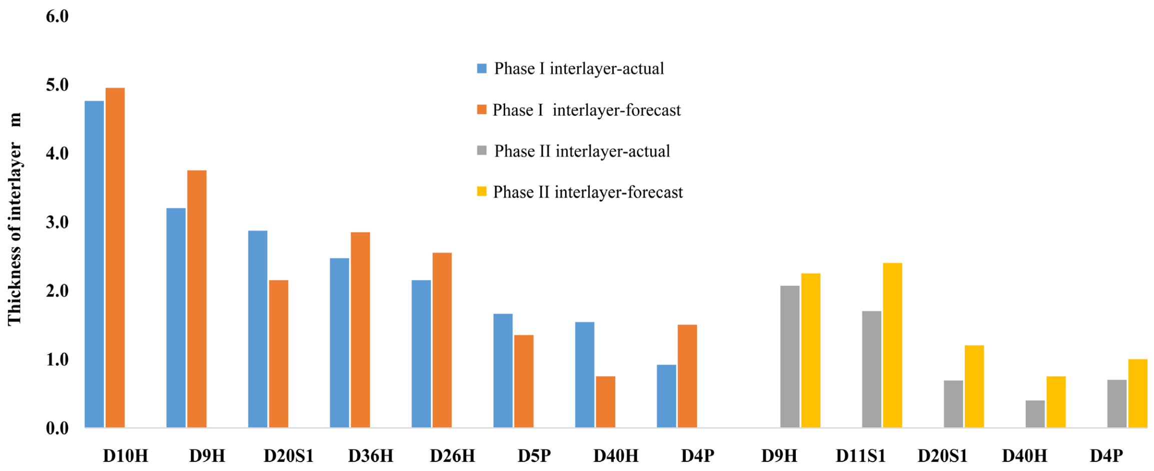

**Figure 6.** Statistical histogram of prediction error of two main interlayer of the NgIII down.

shows that for the interlayer with a thickness of more than 1.5 m, the relative error within 20% accounts for more than 75%, and only a few thin interlayer above the well (thickness less than 1.5 m) have a large error, indicating that the overall prediction result of the interlayer has high reliability.

The NgIII down is the deepest development layer series in the oilfield, and there are few drilled wells. Therefore, rich dynamic production data are used to verify the interlayer inversion results. Taking well D19H as an example, the trajectory of the horizontal section of the well is located in a small layer. The production characteristics are that the water cut rises slowly, and the water cut slowly breaks through to 60% after one and a half years of production. The water cut curve is of "slow climbing" type, which is significantly different from the non shielding type, indicating that there is a large range of interlayer shielding in the lower part, and the water cut breaks through after the bottom water flows around. The dynamic response is consistent with the inversion result (Figure 7 and Figure 8).

### 3.4. Characterization Results and Distribution Characteristics of Main Interlayer

There are obvious differences between the two main interlayers at the top of the NgIII down due to hydrodynamic changes, different sedimentary genetic types and different degrees of undercut erosion and erosion of the river channel. Among them, the distribution of interlayer layers in the first stage is relatively stable, which is mainly formed by flood mud. The plane is distributed in blocks in northeast direction, with a wide distribution area and a thickness of 1 - 4 m, forming a wide range of shielding. It is the main interlayer the NgIII down (Figure 8). In the second stage, the interchannel interlayer has small distribution area and thin thickness. It is mainly filled with inter dam mud and abandoned/late stage river mud. Due to the development of "skylight" and the formation of seepage channel, the braided river reservoir presents the structural characteristics of "overall connectivity and internal complexity".

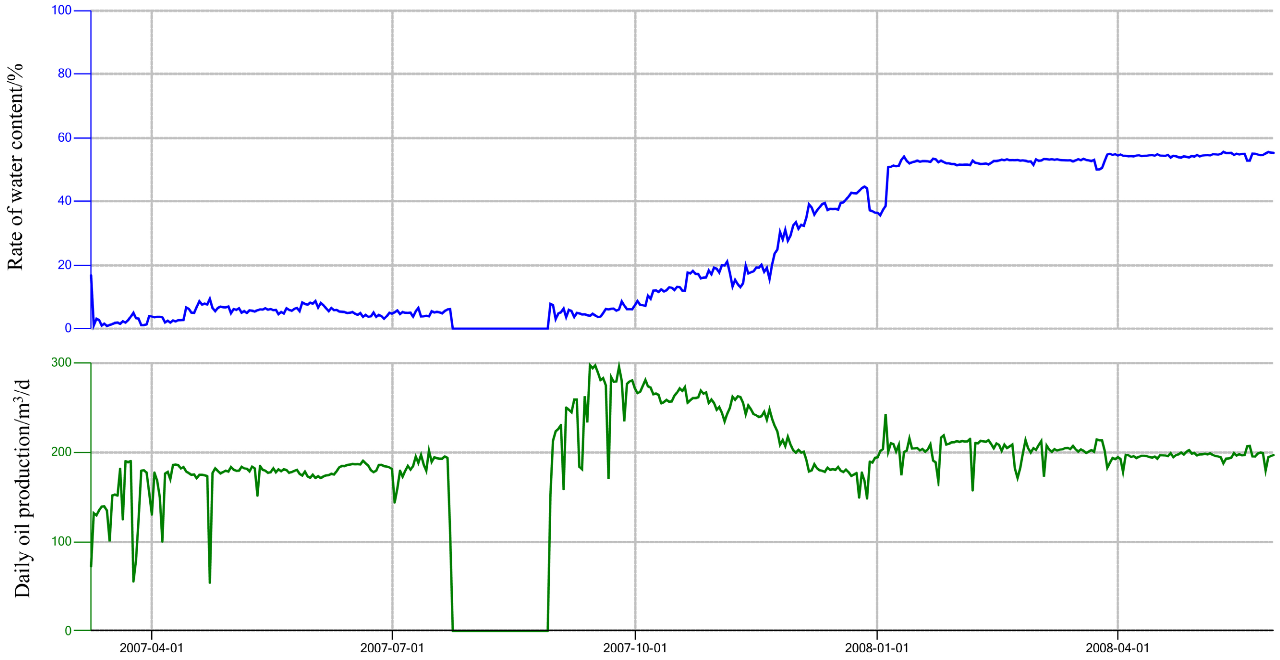

**Figure 7.** The production curve of well D19H.

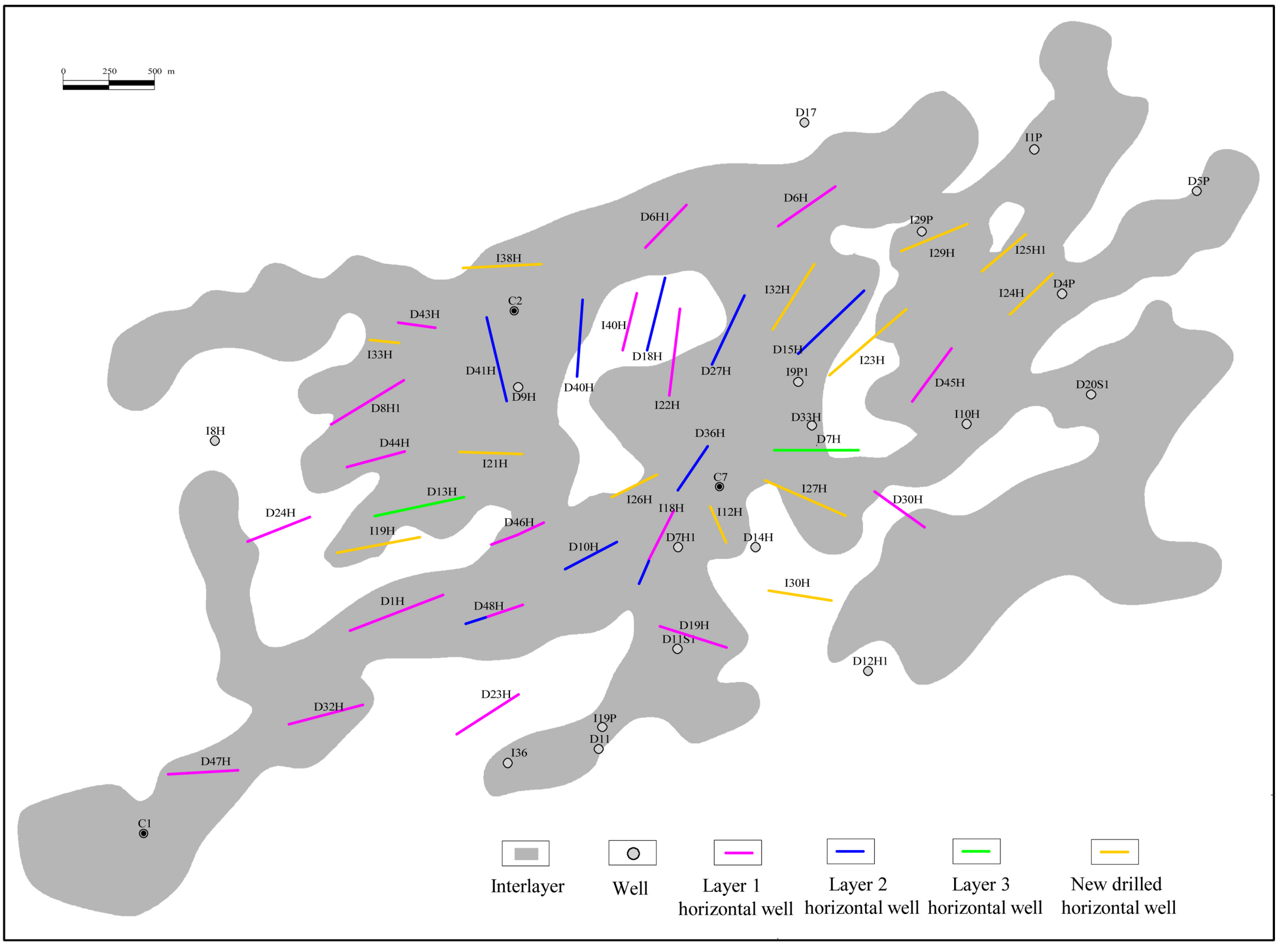

**Figure 8.** Plane distribution of interlayer in first stage of the NgIII down.

## 4. Application and Summary of Achievements

### 4.1. Application of Achievements

Based on the prediction research on the sedimentary stages and distribution range of interlayer, the interlayer in phase 1 has a wide distribution range and large thickness, resulting in strong seepage shielding, which can effectively inhibit the coning of bottom water. In order to avoid the gas cap, the horizontal production wells deployed in the high part of the structure and the gas cap area in the early stage of development are relatively deep in the horizontal section, mainly producing small layers 2 and 3, resulting in the formation of residual oil enrichment area in small layer 1 due to large-area interlayer shielding, which is a favorable area for adjusting and tapping the potential. According to this understanding, 12 development wells were deployed in the lower part of NgIII down from 2019 to 2020, most of which belong to inter well densified wells in small layer 1 at the high part (**Figure 8**). The average daily oil production in the initial stage is 120 $m^3$/day and the water cut is also lower than that of the surrounding old wells. Significant results have been achieved in tapping the potential of bottom water reservoirs with high water cut and high recovery. At the same time, further potential tapping can be further intensified in the future to improve oil recovery.

### 4.2. Summary

Using core, logging and seismic data, according to the genetic type and sedimentary period of interlayer sedimentation, the distribution range of thin interlayers between thick braided rivers is quantitatively predicted by the geostatistical inversion method.

1) Based on the core and logging data and combined with the field outcrop of a sandy braided river, the sedimentary genetic types and sedimentary periods of thick sandstone interlayer of NgIII down are studied, and two stages of interlayer are identified and divided. The interlayer in the first stage is mainly formed by flood mud, which is relatively stable in distribution and is the main interlayer of this layer.

2) On the basis of deterministic inversion and qualitative prediction, the geostatistical inversion method guided by logging constraints and geological knowledge base is used to predict the distribution range of thin interlayer. Through the verification of blind good error and production well reservoir performance, it shows that the prediction result of interlayer greater than 1.5 m has high reliability, which also provides a new idea and method for the prediction of thin reservoir or interlayer of the same type of sedimentation.

3) Based on the interval division and prediction results of the interlayer, the oil-bearing interval at the top of NgIII down is divided into three small layers. The practice shows that the remaining oil enrichment area is formed in the high part of the structure due to the shielding of large-scale interlayer in the layer 1.

## Conflicts of Interest

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

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