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Research on Thin Layer Structure Identification and Sedimentary Facies of Middle and Deep Layers Based on Reflection Coefficient Inversion

—By Taking Dongying Formation of CFD Oilfield in Bohai Offshore as an Example

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Abstract

The sand layer B of Dongying Formation of CFD oilfield in Bohai offshore belongs to the middle deep layer of buried hill overlap deposit. Its reservoir distribution has the characteristics of large burial depth, thin thickness and rapidly lateral change. Because of low resolution of seismic data and overlying sand layer. It is difficult to identify and interpret the structure of sand layer accurately. The uncertainty of structure and reservoir restricts the fine development of B sand layer. In order to identify the top surface of reservoir effectively. The seismic data are processed by using the reflection coefficient inversion method. The results show that the inversion resolution of reflection coefficient is significantly higher than that of original data. The top surface of sand layer B and its overlying sand layer can be well identified and traced. Carrying out structural interpretation of B sand layer based on reflection coefficient inversion data and the microstructure and the formation tip extinction point are implemented. Based on the constraint of new interpretation level, the sedimentary facies plane distribution of B sand layer is described and make prediction of dominant reservoir development area in detail combining with sedimentary paleogeomorphology, along layer attribute section and limited drilling data. The research shows that the study area is mainly from the northwest material sources, the slope belt in the northwest is close to the lake shoreline with a gentle slope and shallow water depositional environment, which is located on the main transport and deposition channels. The shallow water gentle slope landform is suitable for forming large-area sand bar deposition, mainly composed of underwater distributary channel and debouch bars facies, which is the dominant reservoir development area. The research conclusion guides the deployment and implementation of the

development well location effectively.

Keywords

Middle Deep Layer, Braided River Delta, Reflection Coefficient Inversion, Paleogeomorphology, Sedimentary Facies

1. Background

The middle and deep reservoir layers as an important sedimentary which play a key role in oil producing layer within the Bohai oilfield. Generally, the formation is buried at a big depth and due to the particularity of offshore oilfield development, in addition to the lack of drilling data and low resolution of seismic data. All these reasons make the study and analysis of the reservoir very complex. The accurate understanding of structure and reservoir has become the key to restrict oilfield development. At present, scholars have carried out a lot of research work in the aspects of paleoseismic facies control and reservoir restoration [1]-[13]. However, due to the influence of formation absorption attenuation, interference and tuning, the signal-to-noise ratio of seismic data in the middle and deep layers are generally low, which leads to the problems of multi solution and low accuracy in the study of structures and reservoirs, especially in some thin layers of the middle and deep layers.

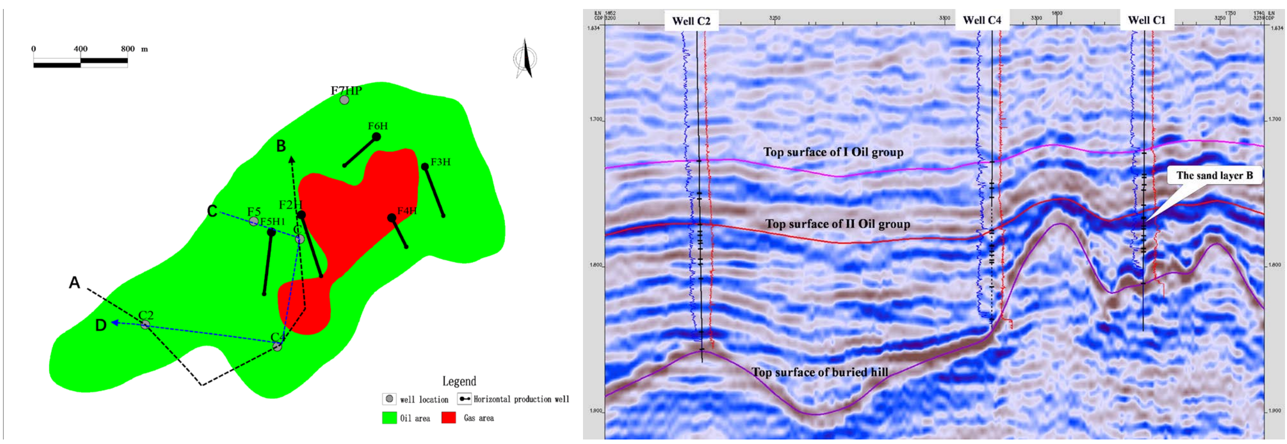
The inversion method based on reflection coefficient is developed in recent years, which can effectively distinguish thin layers and improve the resolution [14] [15] [16]. The reflection coefficient volume obtained by this inversion method can effectively eliminate the thin layer interference phenomenon in the original seismic reflection, and has the advantages of not depending on the well and requiring the initial model, which can improve the seismic data resolution to an extremely high level. However, the inversion results are easy to be disturbed by noise, and the matching between the results and well data is poor, which affects the application effect.

In addition, seismic sedimentology method has unique advantages in describing the plain distribution prediction of sedimentary body, but its results are often constrained by the accuracy of the structural horizon. Aiming at the problem that the structural top of sand layer B in Dongying Formation of CFD oilfield can not be identified and traced, the reflection coefficient inversion method of time-varying wavelet is used to inverse the broadband reflection coefficient body and calibrate the synthetic record. On this basis, the interpretation of stratigraphic structure and seismic sedimentology is carried out again to depict sedimentary facies belt and dominant reservoir area, and to guide the deployment of oilfield well location.

2. General Situation of Oilfield

CFD oilfield is geographically located in the Western Bohai offshore and structurally located in the southeast end of Shaleitian uplift. It is a draped anticline developed on the background of basement uplift. Controlled by the buried hill paleogeomorphology, the structure of Dongying Formation is NE-SW strike (Figure 1). The main oil-bearing series are Neogene Minghuazhen Formation, Guantao formation and Paleogene Dongying Formation, and the buried depth of oil and gas reservoir is 1090 - 2100 m. The Shaleitian uplift is surrounded by Qikou, Nanpu, Bozhong and Shanan oil generating sags, which have good hydrocarbon accumulation conditions.

The main target layer of the oilfield is Paleogene Dongying Formation II oil formation with a thickness of 30 - 120 m. It is a buried hill drape deposit and belongs to discerning River delta sedimentary environment. Controlled by sedimentary base level cycle and material source supply, multi-stage sand formation is developed. Stable mudstone interlayer of 4 - 6 m is developed between sand layers to separate fluid system. The Sand layer B is the main reserve and development unit of the oilfield with buried depth of 2070 - 2100 m. The reservoir thickness is 3.5 - 10.8 m and the average thickness is about 6 - 8 m. The horizontal variation is fast, the overall heterogeneity is strong on the plane, and the unstable physical property interlayer is developed vertically (Figure 2). The



(a) (b)

Figure 1. Well location and cross well seismic profile of sand layer B in Dongying Formation of CFD Oilfield (A - B on the left for section line).

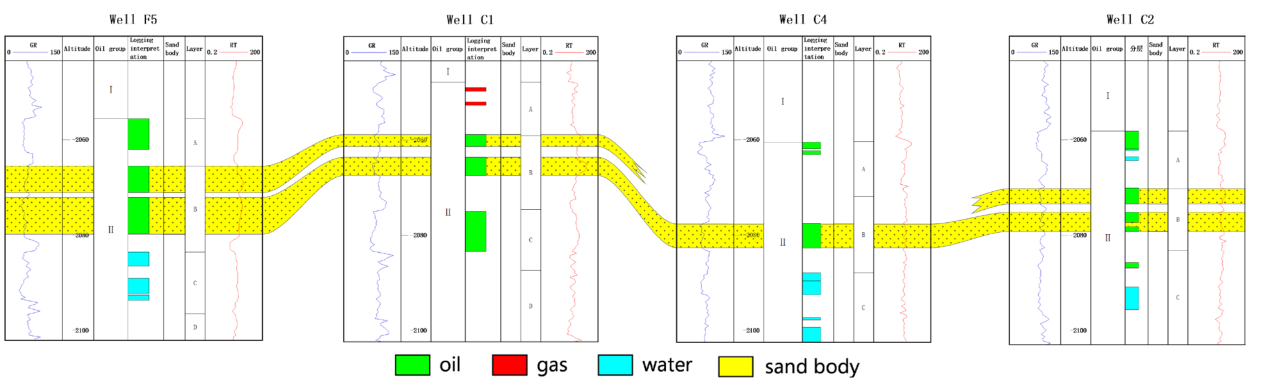


Figure 2. Contrast section of sand reservoir B in CFD oilfield (C-D in Figure 1 for section line).

effective bandwidth of Dongying Formation seismic data is about 15 - 75 HZ and the dominant frequency is 40 HZ, and the vertical resolution is about 12 - 15 m.

The oilfield is in the early stage of development with only 6 drilled wells and 5 horizontal production wells. The well spacing is 500 - 800 m. At present, the development is mainly faced with two problems: 1) Due to the limited resolution of seismic data, the big buried depth of formation and the influence of attenuation and thin layer interference, the sand group presents a complex wave reflection feature on the seismic profile. It is difficult to accurately identify and interpret the microstructure and formation pinch out line of the target layer. Only the thickness conversion method of oil group top surface can be used for mapping and there is a certain uncertainty in the structure. 2) The productivity of production wells is quite different. The daily oil production of high-yield wells is 80 - 150 m^3/d, while that of low-yield wells is only 10 - 20 m^3/d and some wells even have no production. Therefore, it is necessary to carry out the plane sedimentary facies distribution research to find the "sweet spot" area of reservoir.

In order to solve the two problems about the structure is not implemented and the reservoir research is not deep, the seismic data reflection coefficient inversion is carried out to improve the vertical resolution. Effectively identify the top surface of the target layer and the exposed area of the buried hill, and carry out the fine structure interpretation and Paleogeomorphology restoration again. Combined with core and logging data, constrained by the new interpretation surface, the seismic attributes along the formation are extracted, and the sedimentary facies belt and favorable reservoir development area are depicted in combination with sedimentary model.

3. Method of Seismic Reflection Coefficient Inversion

3.1. Basic Principles of Seismic Reflection Coefficient Inversion

Rayleigh criterion considers that the resolution limit of a reflection wave is 1/4 wavelength, which has been widely accepted in geophysical field. Widess thinks that the seismic resolution limit is 1/8 wavelength. For the widess model, the amplitude of seismic spectrum in frequency domain reaches the maximum at 1/4 wavelength. When the layer is thin to 1/8 wavelength, the seismic waveform and frequency will not change significantly, and the amplitude decreases gradually. According to the relationship between reflection coefficient and impedance, it can be seen that the reflection coefficient of wedge-shaped body is positive at the top interface and negative at the bottom interface, and their absolute values are equal. The single sand body wedge model is the simplest geological model, which is quite different from the actual geological model. Tirado designed a reflection coefficient model which is more close to the actual stratigraphic pattern, and decomposed it into odd part and even part. This model is more consistent with the actual stratigraphic variation characteristics.

Any pair of reflection coefficients can be decomposed into the sum of odd and even components. The odd component consists of a pair of equal and opposite reflection coefficients, and the even component consists of two reflection coefficients of the same polarity [17] [18] [19] [20] (**Figure 3**). In the forward modeling of this kind of model, the amplitude of odd component sample sequence first increases with the decrease of layer thickness, and then decreases with the decrease of layer thickness until the layer thickness decreases to zero, and the turning point in the middle is the resolution limit of 1/4 wavelength; the amplitude of even component sample sequence increases with the decrease of layer thickness, and reaches the maximum value when the layer thickness decreases to zero The overall variation characteristics of the model are related to the proportion of the two components, while the peak frequency variation characteristics of the two components are consistent, both increase with the decrease of the thickness, and the total peak frequency will decrease when it is less than 1/4 of the wavelength thickness, and then tend to be stable. It indicates that it is possible to identify thin layer with thickness less than 1/4 wavelength from seismic response [20] (**Figure 4**). Because of the certainty of the variation law of the peak amplitude and peak frequency of the odd and even components with the layer thickness and the determination of the dominant frequency of the seismic data, for the seismic model with single layer thickness and the thin layer thickness smaller than the tuned thickness can be accurately predicted by the way of odd and even decomposition. After odd and even decomposition of reflection coefficient, there is a definite relationship between the dominant frequency of odd component and even component and the thickness of ground layer. Through this relationship, the thickness can be predicted when the dominant frequency is known.

The difference between reflection coefficient inversion and conventional

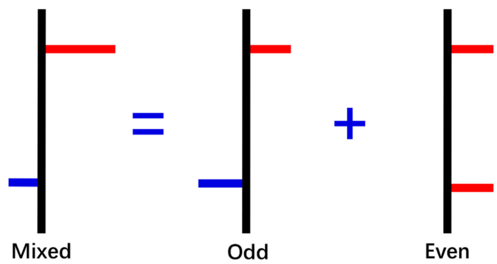


Figure 3. Reflection coefficient odd even decomposition (Cited from [20]).

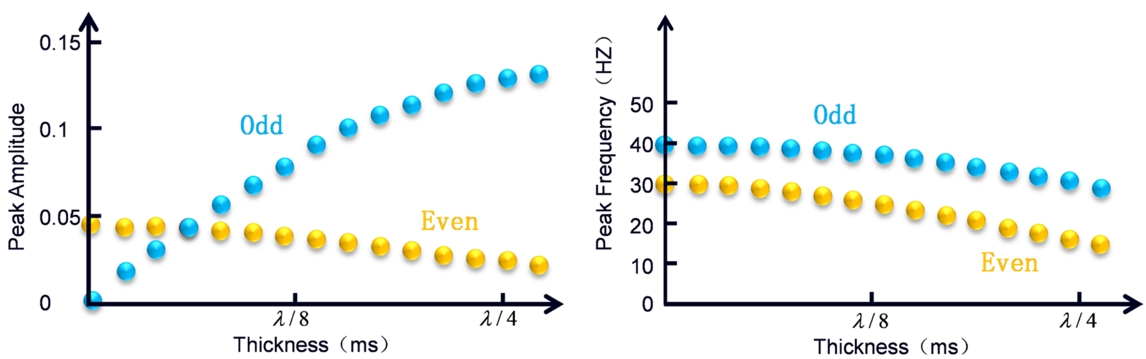


Figure 4. The relationship between the peak amplitude, peak frequency and thickness of odd and even components (Cited from [20]).

inversion is the establishment of the objective function. In the inversion process, the effective optimization algorithm is used, and the logging data is used to constrain. The basic process is to remove the influence of time-varying wavelet according to the broadband seismic signal obtained by frequency extension processing, and the reflection coefficient obtained is taken as the initial reflection coefficient sequence, and then the objective function is solved to obtain the optimal target Reflection coefficient.

3.2. Practical Application Effect

The specific process is as follows: firstly, on the basis of seismic data denoising, the time-varying wavelet is extracted and the odd and even parts of the reflection coefficient are extracted. According to the method of calculating the initial reflection coefficient, the high frequency components and the odd and even reflection coefficients are inversed. Finally, the weight function is used to combine the whole broadband reflection coefficient volume. Compared with the conventional sparse pulse inversion, the reflection coefficient inversion is more sensitive to the thin layer tuning effect, which can effectively eliminate the thin layer tuning effect, and has strong anti noise ability.

From the actual section comparison (Figure 5), the seismic resolution of the processed results is improved. The seismic reflection characteristics of a set of low-frequency complex wave troughs on the top surface of Dongying Formation II oil formation in the original data are transformed into two troughs and one peak reflection, showing two sets of reservoir reflection characteristics. After well seismic calibration and comparative analysis, the upper trough corresponds to the top surface of sand formation A in the II oil formation, and the lower trough corresponds to the top surface of sand formation B. The results show that there is a good corresponding relationship between well and seismic data. According to the calibration results, the fine interpretation of the top structure of sand layer B is carried out again, and the pinch out position of structure and stratum was determined.

From the comparison before and after the structural map, the map is interpreted according to the reflection coefficient inversion method. The overall structural

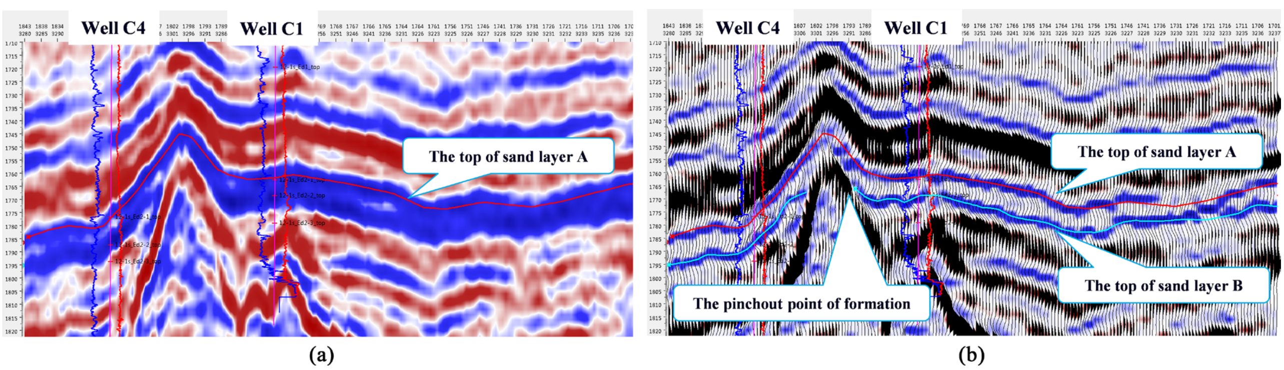


Figure 5. Profile comparison before and after processing by seismic reflection coefficient inversion of sand layer B in Dongying Formation of CFD Oilfield. (a) original seismic section; (b) reflection coefficient inversion section.

trend and shape are basically consistent with the old map, but the local structural description is more refined, and the understanding of the buried hill exposure range within the oilfield scope is more clear, so as to effectively avoid the structural risk (Figure 6).

4. Study on Reservoir Sedimentary Facies

4.1. Restoration of Paleogeomorphology

The sand layer B is a middle deep buried hill overburden deposit, and provenance supply and paleogeomorphology have obvious control on the distribution of sand bodies and sedimentary facies. According to the principle of sedimentary compensation, without considering the differential compaction, the present residual thickness can roughly reflect the change of accommodation space, that is the relative height of paleotopography. Therefore, on the basis of stratigraphic framework division and fine structural interpretation of target horizon, the residual thickness method is used to restore the relative paleotopography.

During the sedimentary period of sand layer B, the paleogeomorphology of the study area is characterized by "high in the north and low in the South", and five types of paleogeomorphology are mainly developed: uplift, steep slope, gentle slope, valley and marsh land. Some ancient high points and slopes are developed in the oil field. The depositional margin is mainly from northwest, and the braided river delta front is formed after the oil field enters the lake (Figure 7).

4.2. Study on Sedimentary Facies

4.2.1. Characteristics of Core and Single Well Facies

Combined with the lithology and logging data of coring wells, the lithofacies and

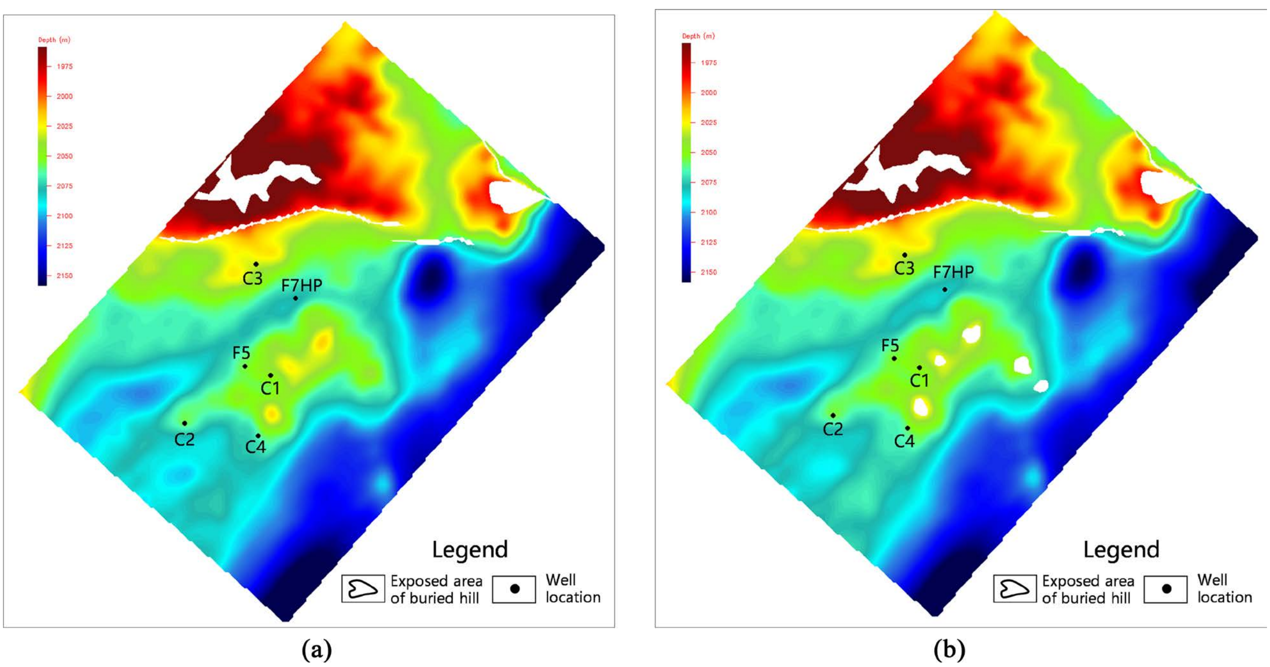


Figure 6. Top structure of sand layer B in the study area. (a) old structural map (conversion); (b) new structural map.

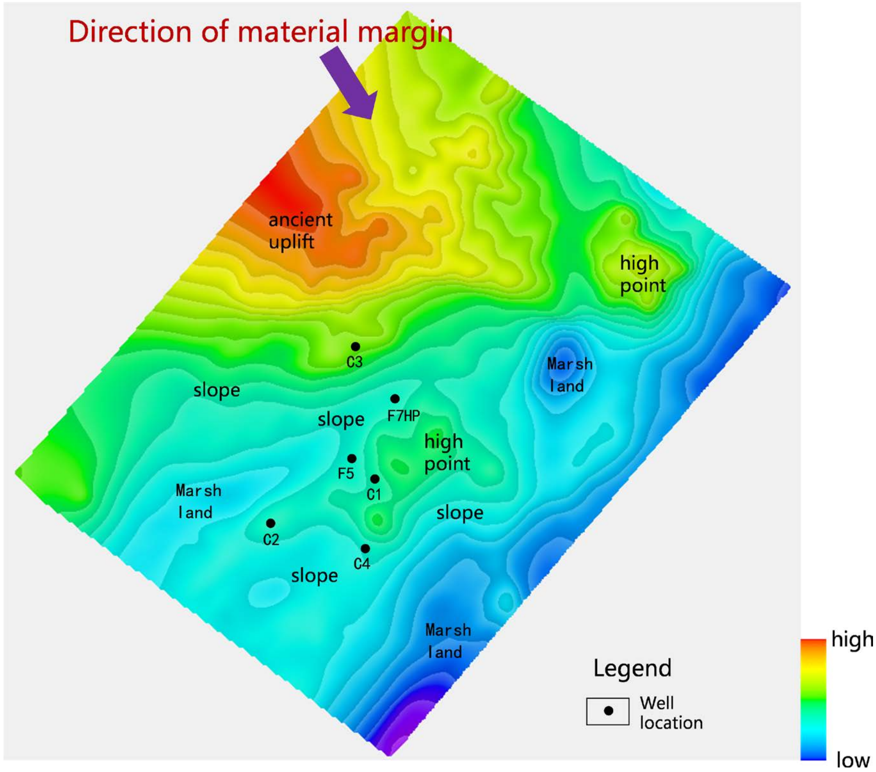


Figure 7. Relative palaeogeomorphology of sand layer B in the study area.

main sedimentary microfacies of Dongying Formation in the study area are analyzed and summarized. Five lithofacies are mainly developed in the study area, namely layered medium fine gravelly sandstone, massive fine sandstone, wavy bedding argillaceous siltstone, massive grayish green mudstone and massive purplish red mudstone (Figure 8).

The logging facies features mainly include low amplitude flat type, medium high amplitude funnel type, medium low amplitude bell type and composite type. The whole shows that the sand formation B of Dongying Formation is mainly composed of braided river delta front sediments, and five types of sedimentary microfacies are mainly developed, such as the main body of the debouch bar, the edge of the bar, distributary channel, interdistributary bay and shallow lake mud of the pre Delta (Figure 9).

4.2.2. Characterization and Distribution Characteristics of Sedimentary Facies

Stratigraphic attribute slicing based on seismic sedimentology theory is an effective means to interpret and characterize sedimentary microfacies. In this paper, under the constraint of the new interpretation isochronous surface, the stratigraphic slices are extracted to interpret the seismic sedimentary facies. After screening, the attribute type is selected as the energy type with good correlation with the sand thickness. From the attribute slice, it can be found that the attribute is in good agreement with the trend of paleogeomorphic sedimentary system, and a number of sedimentary bodies similar to lobophylls are developed

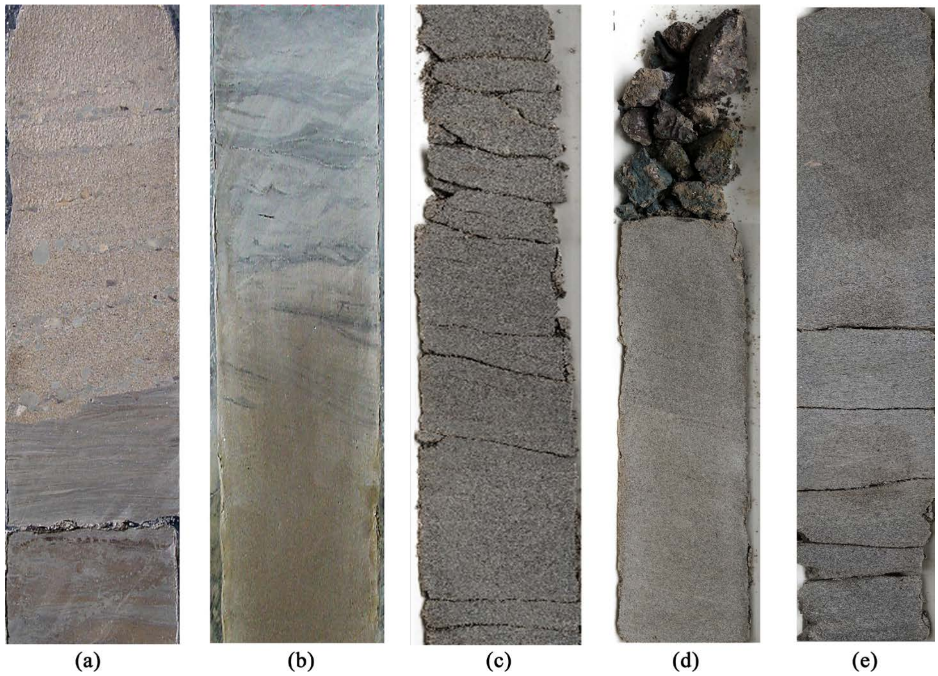


Figure 8. Main feature of lithofacies of Dongying Formation in CFD Oilfield. (a) Layered medium fine sandstone with gravel arranged nearly horizontally, scouring surface developed at the bottom, dark gray mudstone at the lower part (well C2, 2079.6 - 2088.0 m); (b) Massive grayish green mudstone with silt locally (well C2, 2098.3 - 2098.7 m); (c) Dark gray thick fine sandstone with reverse rhythm from bottom to top, massive bedding (well F7HP, 2155.3 - 2155.7 m); (d) Grayish green mudstone at the upper part and the lower part is massive fine sandstone (well F7HP, 2160.3 - 2160.7 m); (e) Light gray medium fine sandstone with less argillaceous content, reverse cycle grain size, massive bedding (well F7HP, 2160.7 - 2161.1 m).

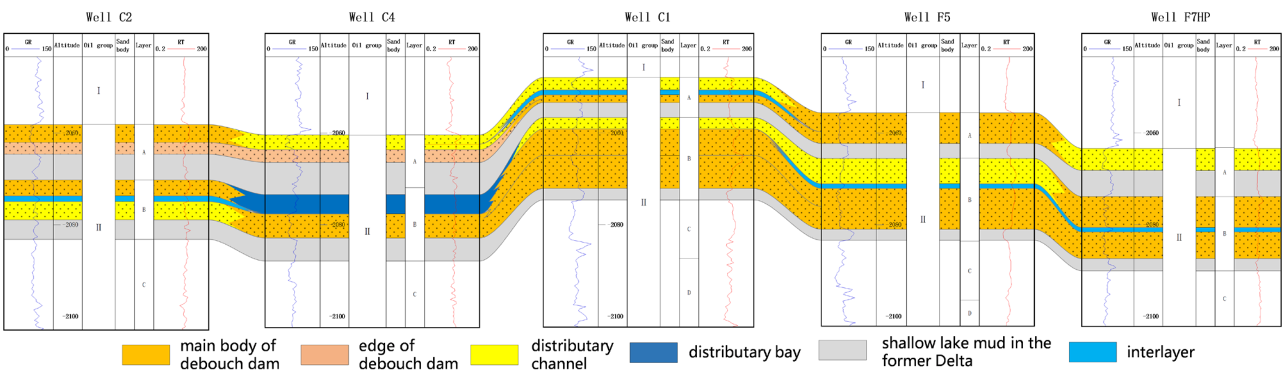


Figure 9. Profile of sedimentary connecting well of Dongying Formation in CFD oilfield (sand layer A and B).

in the south side, which is in line with the depositional model of Delta into the lake (Figure 10 and Figure 11).

Based on the characteristics of paleogeomorphology, single well facies and seismic attribute slices, and combined with the sedimentary model of braided river delta, the plane distribution of sedimentary microfacies in the study area was studied. During the depositional period of sand layer B, the sedimentary area was mainly controlled by the provenance of the Shaleitian paleouplift in the northwest direction, and developed a number of striped distributary channels

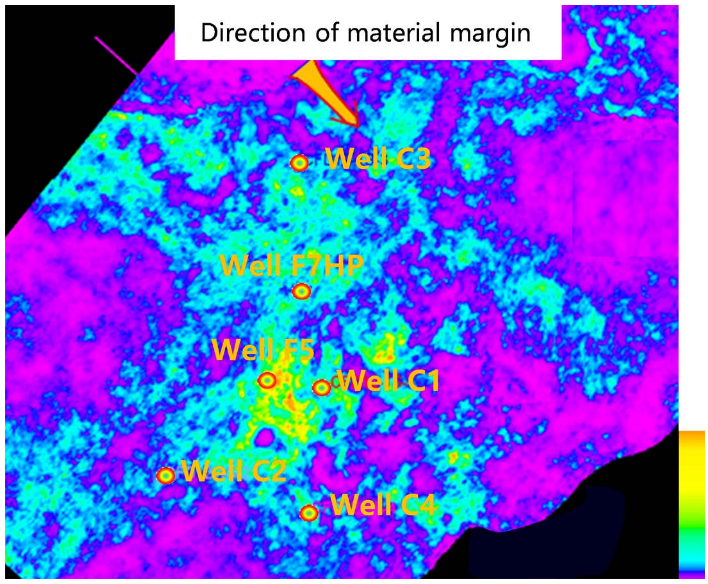


Figure 10. Seismic horizon slice of average energy attribute (time window 6 ms).

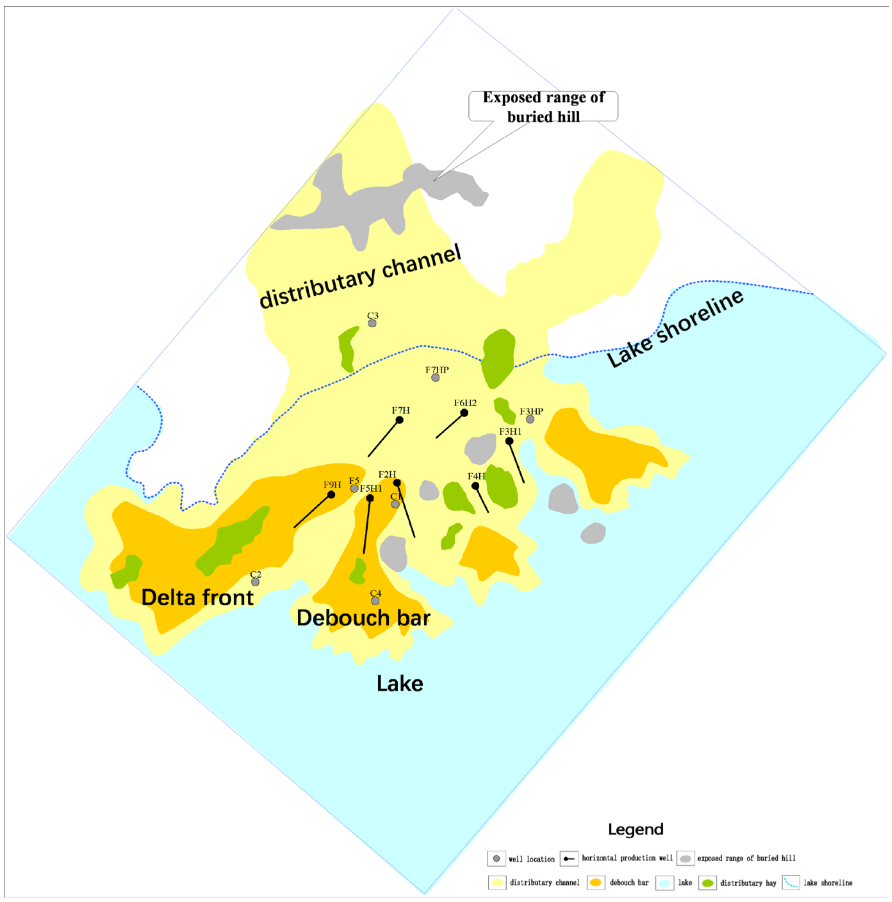


Figure 11. Distribution of sedimentary facies of sand layer B in the study area.

and lobate sand bar sedimentary bodies. The main sedimentary microfacies are the main body of the mouth bar, the edge of the bar, the distributary channel and the mud of the pre Delta. The main body of the mouth bar and the distributary channel are the main component, and the debouch bar is lobate. They are distributed in the South and southwest of the oilfield.

5. Application and Summary

5.1. Application of Achievements

Based on the study of paleogeomorphology and sedimentary facies distribution, the reservoir development of drilled wells under the control of multiple factors is systematically summarized (Table 1). It is considered that during the deposition period of sand layer B, the northwest slope zone of the study area is close to the lake shoreline, with gentle slope, shallow water body and large sediment accommodation space. It is located on the main sediment transport channel, where the sediment is unloaded first and shallow water is gentle slope The main sedimentary facies are underwater distributary channel and mouth bar. The seismic reflection generally shows medium strong amplitude. The reservoir is thick and has good physical properties. It is the dominant reservoir development area in the study area.

Based on this understanding, the oilfield deployed and implemented two horizontal production wells F7H and F9H in the west slope zone of the sand body in 2020. The average drilling encounter rate of the two wells in the horizontal section is 86%, and the initial oil production is 70 - 90 m^3/d, which has achieved good development adjustment effect, and also verified the geological understanding.

5.2. Summary

1) Based on the principle that even component reflection coefficient can improve the resolution of thin layer, the reflection coefficient profile can be inversed to improve the seismic resolution. On this basis, fine interpretation is carried out to implement the structure, which provides a new research idea and

Table 1. Analysis of main controlling factors of B sand layer in CFD Oilfield.

Well	Well type	Characteristics of paleogeomorphology	Main sedimentary microfacies	Reservoir thickness (m)	Average permeability of reservoir (mD)	Initial daily oil production (m^3/d)
C1	exploratory well	northwest gentle slope	debouch bar	7.4	167	-
C2	exploratory well	ancient high point	distributary channel	4.3	113	-
C4	exploratory well	south gentle slope	debouch bar	5.1	152	-
F5	pilot well	northwest gentle slope	debouch bar	10.9	257	-
F7HP	pilot well	northwest gentle slope	distributary channel	11.4	206	-
F2H	horizontal production well	northwest gentle slope	distributary channel	-	264	78
F3H	horizontal production well	southeast gentle slope	far sand bar	-	102	9
F4H	horizontal production well	southeast gentle slope	distributary channel	-	124	15
F5H	horizontal production well	northwest gentle slope	distributary channel	-	189	37
F6H	horizontal production well	northwest gentle slope	distributary channel	-	313	126

method for improving the resolution of seismic data and fine identification of similar middle and deep reservoir structures.

2) The distribution of dominant reservoirs in the middle and deep layers is often controlled by paleogeomorphology and provenance supply. Based on the analysis of paleogeomorphology, single well facies and seismic attribute slice data, the provenance of sand layer B of Dongying Formation comes from the Northwest Shaleitian uplift, which forms the braided river delta front deposit in the study area. The northwest slope belt is close to the lake shoreline, and is located on the main sediment transport channel. The shallow gentle slope landform is suitable for the formation of large reservoir. The sand bar deposits with continuous area are dominated by underwater distributary channel and mouth bar sedimentary facies, which are favorable areas for the development of dominant reservoirs.

Conflicts of Interest

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

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