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Application of Phase-Controlled Reservoir Prediction Technology in NB Oilfield of Bohai Bay

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Abstract

The shallow oil and gas fields of the Bohai Sea are dominated by fluvial deposition, large lateral variations of the reservoir, and a complex oil-water relationship. Horizontal wells must be deployed within the high quality reservoirs with good physical properties and high permeability so as to improve the productivity of the oil wells. Therefore, the reliability of reservoir prediction becomes extremely important. In this paper, on the basis of analyzing the petrophysical characteristics and seismic response characteristics of the reservoir, we proposed the phase-controlled reservoir prediction technology, which combines reservoir prediction and reservoir cause; studied the distribution law of the high quality reservoirs of the NB Oilfield by using phase-controlled reservoir prediction technology; deployed and drilled the development wells on this basis, and obtained good results.

Key words: Fluvial facies; Reservoir prediction; Phase-controlled; Main parameters of seismic waves

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INTRODUCTION

The NB Oilfield is located in the central waters of Bohai Bay, and currently it is the offshore fluvial facies heavy oil oilfield with the largest degree of development difficulty. The oilfield reservoir belongs to the Upper Neogene Minghuazhen Formation, its lateral connectivity is poor, and the oil-water relationship of the oilfield is very complex. The horizontal wells need to be deployed in the high quality reservoirs with good physical properties and high permeability so as to improve the productivity of the oil wells. Facing the high precision reservoir prediction requirements of the oilfield, we proposed the use of phase-controlled reservoir prediction technology and obtained a good application in the development process for the oilfield. First, we analyzed the petrophysical characteristics and seismic response characteristics of the NB Oilfield reservoir, then macroscopically predicted the spatial distribution of the reservoir by using the seismic multi-attribute neural network analysis technique in combination with the post-stack seismic data; and finally concluded with a study of the distribution law of the high quality reservoirs of NB Oilfield under the control of point bar microfacies by using phase-controlled processing technology; and guided the deployment of the development wells, reducing the risks of the development wells and providing a powerful guarantee for the efficient development of the oilfield.

1. PETROPHYSICAL CHARACTERISTICS OF RESERVOIR

After the analyses of the acoustic logging curves, it could be found that the speed of the sandstone of NB Oilfield is slightly lower than that of mudstone, and there is little difference in the wave impedances of sandstone and mudstone; the studies regarding density logging curves show that the density increases with the increase of gamma, and that low gamma value corresponds to the low density value. That is to say, the density of sandstone is lower than that of mudstone. The density variation range of sandstone is between 1.9 g/cm^3 and 2.1 g/cm^3, while the density variation range of mudstone is between 2.08 g/cm^3 and 2.3 g/cm^3. Thus it can be seen that the density curves are relatively sensitive to the sandstone and mudstone, having good distinguishability (Figure 1).

2. SEISMIC RESPONSE CHARACTERISTICS OF RESERVOIR

The NB Oilfield reservoir is shown as having strong amplitude reflection on the conventional migration seismic profile (Figure 2). The shallow gas is manifested as a very strong wave with a trough-wave peak on the seismic profile, and it can be identified with bright spots; the oil layer is also exhibited as strong with wave trough-wave peak on the seismic profile, while the reflection of the deep water layer on the seismic profile is relatively weak.

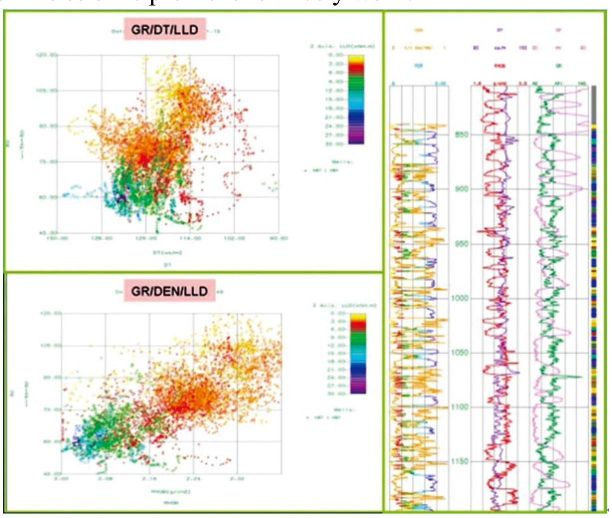

Figure 1
Sensitivity Analysis of Logging Curve

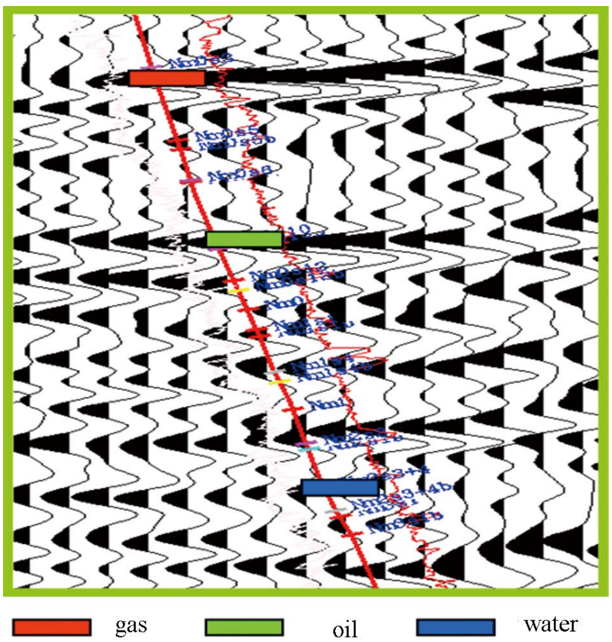

Figure 2
Through-Well Seismic Profile

3. MULTI-ATTRIBUTE NEURAL NETWORK INVERSION

In this paper, we used the probabilistic neural network to establish the statistical relationship of logging information with various seismic attributes; Extrapolated the logging curves from the seismic attributes calculated by the seismogram based on the statistical relationship; and obtained various reservoir parameters. The method overcomes the multiplicity of the result caused by seismic wavelets and the initial geological model establishment, and the prediction result was more in line with the actual situation.

Assuming that the input sample is the seismic attribute A_{ij} (i = 1, 2,…, M; j = 1, 2,…, N), A_{ij} is the j-th sampling point of the i-th seismic attribute. The output logging curve is L_j (j = 1, 2,…, N), and L_j is the value of the j-th sampling point on the target logging curve. For the given training sample, the new output logging curve value can be written as the linear combination of the logging curve in the training data. The new data sample is as follows: $X = \{A_{1j}, A_{2j},\dots, A_{Mj}\}$. The output logging curve value can be obtained through the following formula:

$$\hat{L}(x) = \frac{\sum_{j=1}^{n} L_j \exp[-D(x, x_j)]}{\sum_{j=1}^{n} \exp[-D(x, x_j)]}$$

where: $$D(x, x_j) = \sum_{i=1}^{M} \left[\frac{x_i - x_{ij}}{\sigma_i} \right]^2$$

$D(x, x_j)$ is the variable quantity between each training sample x_j and input point, σ_i is the smoothing parameter, and x_{ij} represents the i-th attribute of the j-th sampling point. The purpose of the training network is to determine σ_i, and the criterion of determining σ_i is the minimum calibration error of the entire network, namely, minimum error between the actual log values and the predicted log values. The seismic attributes registered before the minimal value of the calibration error are the optimal attribute combinations.

We randomly selected eight attributes, and conducted analyses for the #6 well of the NB Oilfield. The results show that wave impedance reciprocal, amplitude envelope, 25/30-35/40 Hz band pass filtering and amplitude-weighted instantaneous phase cosine are the optimal attribute combinations. Neural network training was conducted with the four optimal attribute combinations with the training samples and the density logging curves as the target samples. The results show that the consistent degree of the predicted logging curve of #6 well with the original logging curve is high, and the correlation coefficient reaches 83%.

Figure 3 shows the contrast between the results after the drilling of the development wells and the seismic inversion profile. The red events in the figure are the sandstone, and the logging curve is the resistance curve. NB7 well is the appraisal well, as it participated in the seismic inversion, and all the other wells are development wells drilled after the inversion. As can be seen from the figure, the consistent degree of the seismic inversion profile with the actual drilling results is high.

Figure 4 shows the contrast between the drilling trajectory of the horizontal well B1M and the seismic inversion profile. The law of clear channel sand body distribution can be seen in the figure. The red areas are the areas where the reservoir has good physical properties. According to the research results, the B1M well was deployed along the distribution direction of the sand bodies with good physical properties. Totally one main branch (A) and three branches (B, C and D) were drilled for B1M well. In the horizontal section, the drilled oil layers reach 98%, and among them, the good reservoirs reach 95.4%. The drilled mudstone and poor reservoirs are located in the middle of the horizontal section.

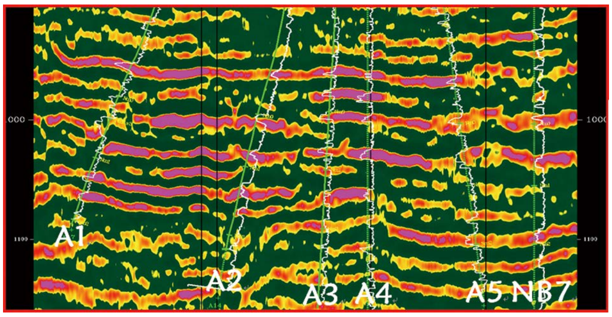

Figure 3
Contrast Between Results After Drilling of Development Wells and Seismic Inversion Profile

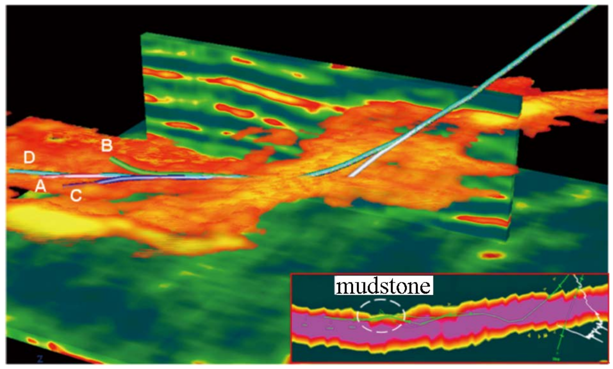

Figure 4
Contrast Between Drilling Trajectory of Horizontal Well B1M and Seismic Inversion Profile

4. PHASE-CONTROLLED RESERVOIR PREDICTION

In this paper, we conducted phase-controlled processing on density data volume predicted by the multi-attribute neural network, and carried out the separations for the point bar sand bodies and other sedimentary microfacies sand bodies, which improved the resolving effect for the single point bar sand body.

The phase control refers to the fact that the sedimentary microfacies have certain control actions within some geophysical parameters, or the fact that the speed, density, wave impedance and other parameters of the sedimentary microfacies follow certain laws as depth changes. The speed, density, wave impedance and other geophysical parameters can be obtained through seismic inversion. By using the phase-controlled principle, various sedimentary microfacies information can be extracted from the geophysical parameter data volume, or the separation and prediction can be conducted for various sedimentary microfacies. Figure 5 shows the prediction process used by the phase-controlled.

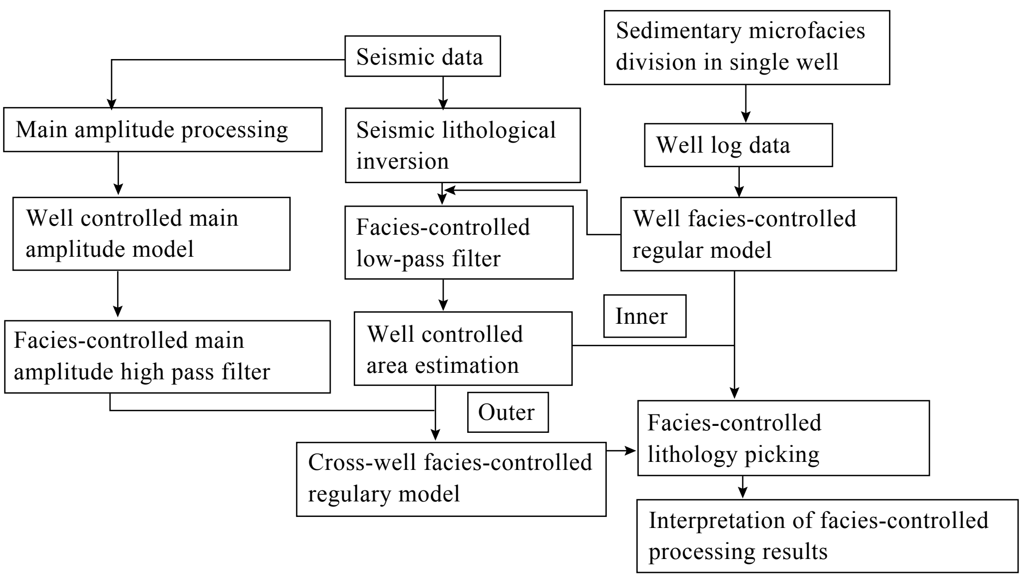

Figure 5
Phase-Controlled Processing Flow

The phase-controlled law analysis is key for the phase-controlled reservoir prediction. On the basis of studying the relationship between sedimentary microfacies of the NB Oilfield and geophysical parameters, we summarized the following phase-controlled laws of the NB Oilfield: The point bar is the main control sedimentary microfacies of the phase-controlled role, and the density is the main control parameter among various geophysical parameters; the density under the control of the point bar microfacies satisfies the mathematical model of the quadratic curve law with the change of depth; the density can also better separate the point bar and other sedimentary microfacies, as shown in Figure 6.

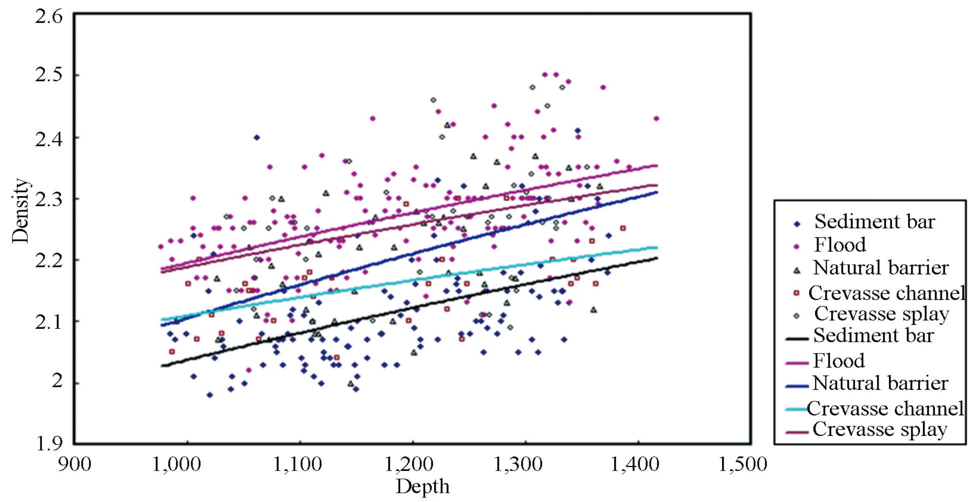

Figure 6
Phase-Controlled Density-Depth Relationship

The processing technique for the seismic main amplitude is the key technique used for forming the phase-controlled model between wells in the phase-controlled processing. Its principles are to use the function of complex energy density, combine the distribution characteristics of signal energy in the time and frequency domains, and establish the time-frequency-space domain characteristic parameter relationship equation of the signal, thereby calculating the seismic waves' main amplitude, main frequency and main phase. The time-space domain seismogram was recorded as x (t, x), and the Hilbert transform was used to constitute the complex seismic trace:

$$u(t,x) = x(t,x) + iy(t,x) = |u(t,x)|e^{i\theta(t,x)}$$

Then the Fourier transform was conducted for the complex trace, with the purpose of finding its spectrum conjugate:

$$\overline{u}(f,x) = |u(f,x)|e^{-i\phi(f,x)}$$

The complex energy density function of time-frequency-time-space domain was constituted:

$$\varepsilon(t,f,x) = |u(t,x)| \cdot |u(f,x)|e^{i[\phi(f,x)-\theta(t,x)+2\pi ft]}$$

According to the principle that the phase during the maximum energy is minimum, the following relational expressions of main frequency and group delay during the maximum energy can be established:

$$\partial[\phi(f,x) - \theta(t,x) + 2\pi ft]/\partial t = 0$$

$$\partial[\phi(f,x) - \theta(t,x) + 2\pi ft]/\partial f = 0$$

After the relational expressions were solved, the main frequency (f_0), group delay (t_0) and main amplitude (A_0) were acquired.

$$f_0 = \frac{1}{2\pi}\frac{\partial\theta(t,x)}{\partial t},\ t_0 = -\frac{1}{2\pi}\frac{\partial\phi(f,x)}{\partial f},\ A_0 = \sqrt{|\varepsilon(t_0, f_0, x|}$$

In order to verify the correctness and feasibility of the phase-controlled reservoir prediction method, we conducted a trial calculation for the theoretical model. The formation of the theoretical seismic profile was based on the density profile, as well as NB5 (Figure 7). The acoustic logging data were provided by using the well section of A oil group of lower member of Minghuazhen Formation, and the theoretical seismogram profile (Figure 8) was synthesized in combination with the extracted seismic wavelets of the seismic traces found near the wells. The main amplitude profile (Figure 9) was obtained through conducting main amplitude processing for the synthesized theoretical seismic waves. The main amplitude energy of a through-well point bar was extracted in combination with the explanation of sedimentary microfacies of the single well. The lower limit of the main amplitude energy was taken for the purpose of designing the high-pass filter, and the phase-controlled high-pass filtering was conducted for the main amplitude to obtain the main amplitude profile (Figure 10), which only reflects the existence of the point par. The statistical point bar density law was used for each well, the upper limit of the density value was taken to design the phase-controlled low-pass filter, and the density profile (Figure 11) in which most sedimentary microfacies except the point bar are separated, could be obtained through conducting filtering for the theoretical density profile. The main amplitude profile of the point bar was used to pick and fit the law of point bar density variation each point between wells on the theoretical density filtering profile, the regulation model was used to conduct the phase-controlled processing for density profile after filtering, and ultimately the point bar density profile (Figure 12) in which other sedimentary microfacies are separated, could be obtained.

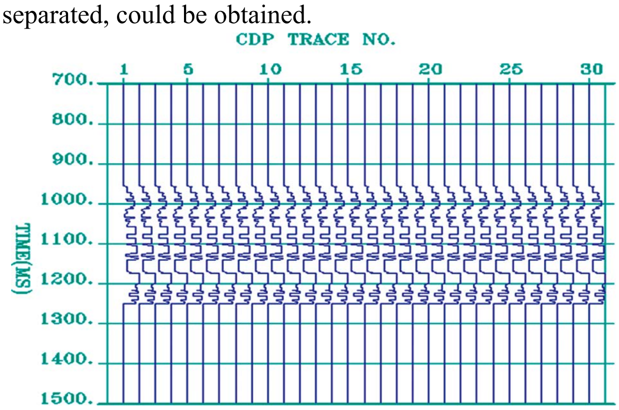

Figure 7
Theoretical Density Profile

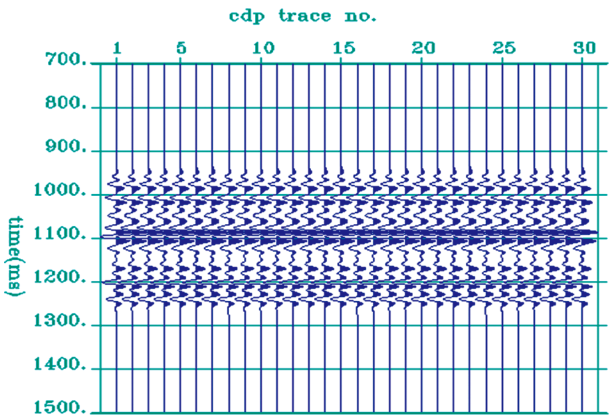

Figure 8
Theoretical Seismogram Profile

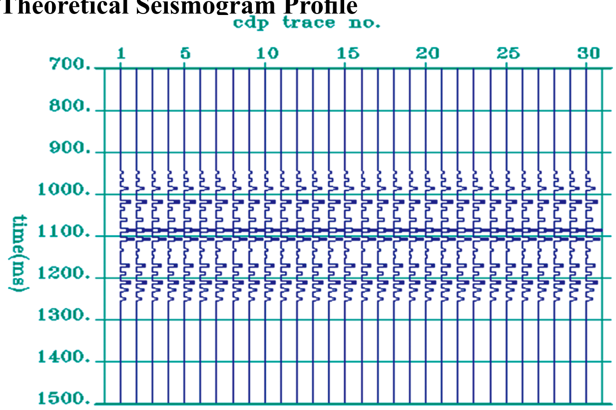

Figure 9
Theoretical Main Amplitude Profile

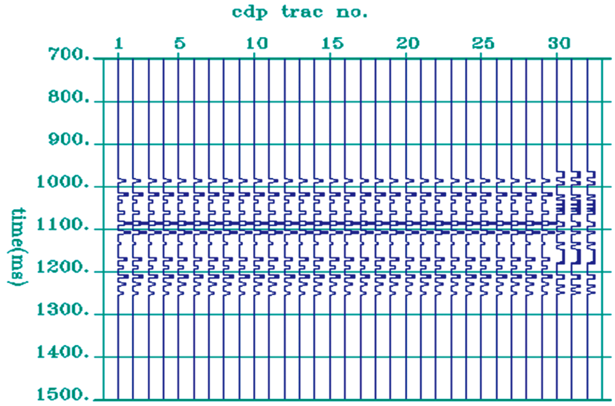

Figure 10
Theoretical Main Amplitude Profile of Point Bar

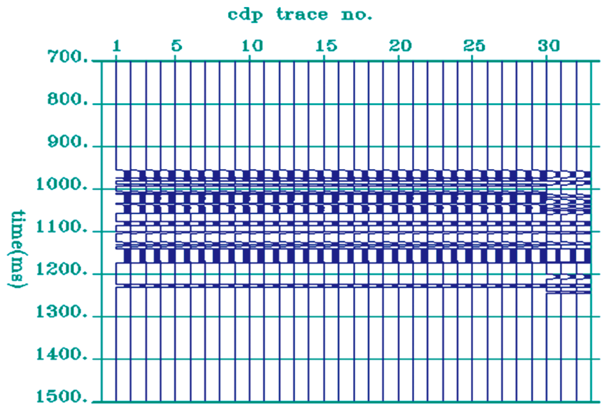

Figure 11
Theoretical Density Filtering Profile

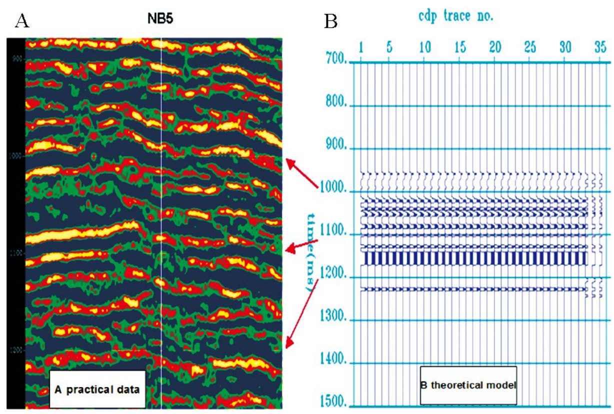

Figure 12
Comparison of Results of Phase-Controlled Processing of Theoretical and Actual Data

In Figure 12, Figure A shows the actual phase-controlled processing profile of the NB5 well, with the red-yellow being the distribution of the point bar; Figure B shows the trial calculation results of the phase-controlled processing of the theoretical model, the blue event represents the point bar, and the two traces on the right side of Figure B reveals the point bar records of the theoretical design. As can be noticed from the figure, the trial calculation results of the theoretical model are fully consistent with the designed theoretical point bar records, essentially a corresponding to the number of the point bars of the actual data processing phase-controlled processing, and thereby verifying the reliability of the phase-controlled algorithm.

On the basis of the theoretical model validation, we used the phase-controlled reservoir prediction method to separate the point bar sand bodies from the other sedimentary microfacies sand bodies. Figure 13 shows the planar distribution of the whole area and of the point bar sand bodies of oil group II, the point bar in the white delineated area is developed, while the point bar in the blue delineated area foregoes development. In the predicted place for the point bar to develop development place, an A10m horizontal branch well was designed (Figure 14), the well successfully drilled the No. 4 sand body of oil group II, and the physical properties of the drilled sand body were good.

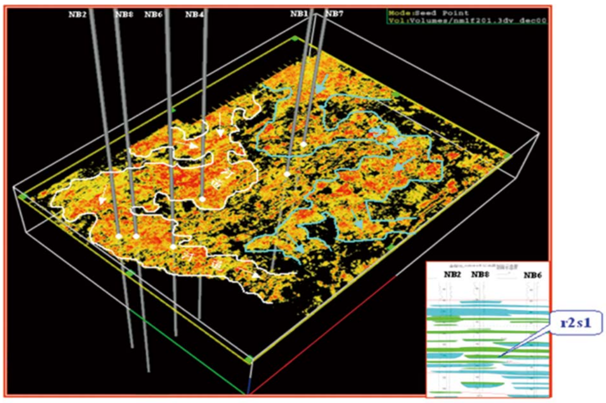

Figure 13
Predicted Planar Graph of Phase-Controlled Point Bar of II Oil Group

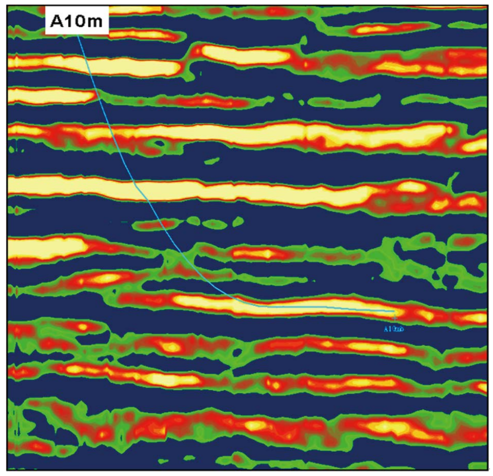

Figure 14
Predicted Point Bar Profile of Through-A10m-Well

CONCLUSION

The phase-controlled reservoir prediction technology combining reservoir prediction and reservoir cause can extract the information from the sedimentary microfacies from the seismic lithology inversion data volume, thereby achieving the separation of the sedimentary microfacies and predicting the spatial distribution law of the favorable sedimentary microfacies reservoir. The trial calculation of the theoretical model verified the correctness and feasibility of the phase-controlled reservoir prediction method; the results from the phase-controlled reservoir prediction of the actual seismic data were confirmed by the development wells, and the good effects were obtained, opening up broader prospects for the development and further application of the phase-controlled processing technology.

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