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Paleogeomorphology of Mixed Rock Deposition in KL16 Oilfield

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Abstract

KL16 (Kenli 16) oilfield is located in Bohai Sea, close to Laizhou Bay depression, with favorable reservoir forming conditions. The lower member of Shahejie Formation (lower sub member of the third member of Shahejie formation) has shallow burial, complex structural sedimentary evolution, diverse reservoir lithology types, and unclear reservoir distribution laws, which restrict the exploration and development process. Comprehensive use of core, seismic, logging and analytical laboratory data, through the combination of structural recovery and stratigraphic recovery, the micro paleogeomorphology of the lower member of Shahejie Formation in the sedimentary period is finely restored, and the sedimentary system and sedimentary model in the study area are defined. The study shows that during the sedimentary period of the lower member of Shahejie formation, four geomorphic units were developed in the study area: uplift, slope, platform and depression; Under the control of paleogeomorphology, three different sedimentary environments are developed: Braided River Delta is developed in the west, shore shallow lake mixed beach bar is developed in the middle, and fan delta is developed in the south. Based on the analysis of regional geology and sedimentary characteristics, the principal component coupling technology based on the constraint of sedimentary facies belt is optimized for reservoir distribution prediction, and the application effect is good.

Keywords

Paleogeomorphology, Mixed Rock Reservoir, Laizhouwan Sag, Reservoir Prediction

1. Introduction

Paleogeomorphology is an erosive and reformed geomorphology or sedimentary filling geomorphology formed by geological processes in the period of paleogeological history. It is an important background factor that controls the development and distribution of sedimentary systems. Its formation and evolution are comprehensively affected by many geological factors, such as basin subsidence, structural transformation, material supply, sedimentary filling, differential compaction in later stages, paleoenvironmental climate, and water base level change [1] [2]. The ancient landform shape has a certain control over the development type of the sedimentary system [3] [4] [5], and the mechanism of the ancient landform on the sedimentary system is mainly manifested in the control of sand body development [6]. Paleogeomorphological restoration helps to reveal the configuration relationship between source sink systems [7], which is the key and foundation for accurate prediction of middle and deep reservoirs. It has become a hot spot in the analysis and research of oil and gas basins at home and abroad to reveal the "constraint effect of paleogeomorphology on the sedimentary system". Although many experts and scholars have done a lot of work in the control effect of paleogeomorphology on the sedimentary system and have obtained a number of important research results and understandings, most of these results and understandings are concentrated in the study of macro paleogeomorphology, and the study of micro paleogeomorphology in local areas is still relatively weak. On the basis of macro structural paleogeomorphology, restoring the micro paleogeomorphology of local areas and characterizing the distribution characteristics of micro geomorphic units are crucial to reveal the distribution law and distribution range of dominant sand bodies, further carry out effective reservoir prediction and improve the implementation effect of horizontal wells [8] [9] [10].

KL16 oilfield is located in the South Sea area of Bohai Sea. Structurally, it is located in the gentle slope zone in the south of Laizhouwan sag, with great exploration and development potential. The main target layer in the study area is the lower Sha 3 member, where different sedimentary systems are distributed alternately. The mixed rock is extremely developed, the reservoir thickness is thin, and the distribution law of favorable reservoirs is unclear, which restricts the development process of the study area. In this paper, using seismic, logging and analytical laboratory data, combined with the regional geological background, through the method of combining structural recovery and stratigraphic recovery, the micro paleogeomorphology of the lower Sha 3 member in the study area of kl16 oilfield is finely restored, and its control over the depositional system and depositional mode is revealed. The principal component coupling reservoir prediction technology based on the constraint of sedimentary facies is optimized to extract sensitive seismic attributes and predict the distribution of reservoirs of different lithology, It effectively guided the implementation of the development plan of the research area.

2. Geological Background of the Study Area

Laizhouwan sag is located in the southern sea area of Bohai Sea. It is a Cenozoic dustpan fault depression sandwiched by the Tan Lu fault zone and formed on the Mesozoic basement. With an area of about 1780 km^2, it is a secondary structural unit of Bozhong depression. The depression is adjacent to Ludong uplift in the East, Weibei uplift in the south, West Branch of Tancheng Lujiang strike slip belt in the West and laibei low uplift in the North (Figure 1).

KL16 oilfield is located at the high part of the gentle slope belt at the edge of Laizhouwan depression basin. Under the influence of tectonic uplift, the buried depth of Es3 is about 1600 m. The southern slope belt mainly presents a high angle slope belt lifted by tilting from north to south. The Paleogene Shahejie Formation and Dongying Formation in the southern slope belt and the overlying Neogene Guantao formation are in a high angle unconformity relationship, which shows obvious cutting characteristics. Part of the strata in the lower sub member of Sha 3 are denuded (profile a in Figure 2). The current structure shows that the buried hill deformation is relatively strong, and the western block of the oilfield has been uplifted under the influence of the structure. The denudation is obvious. The eastern block is affected by tectonism, and the stratum is obviously subsidence [11] (Figure 2 Section B).

The lower member of Es3 in the study area is the main oil-bearing horizon. Two types of reservoir lithology are developed in the lower member of Es3: shore shallow lake to semi deep lake facies beach bar sand, lacustrine carbonate mixed rock and delta sedimentary sandstone. Among them, the mixed rocks are mainly thin interbeds, the thickness of single layer is less than 2.0 m, and the

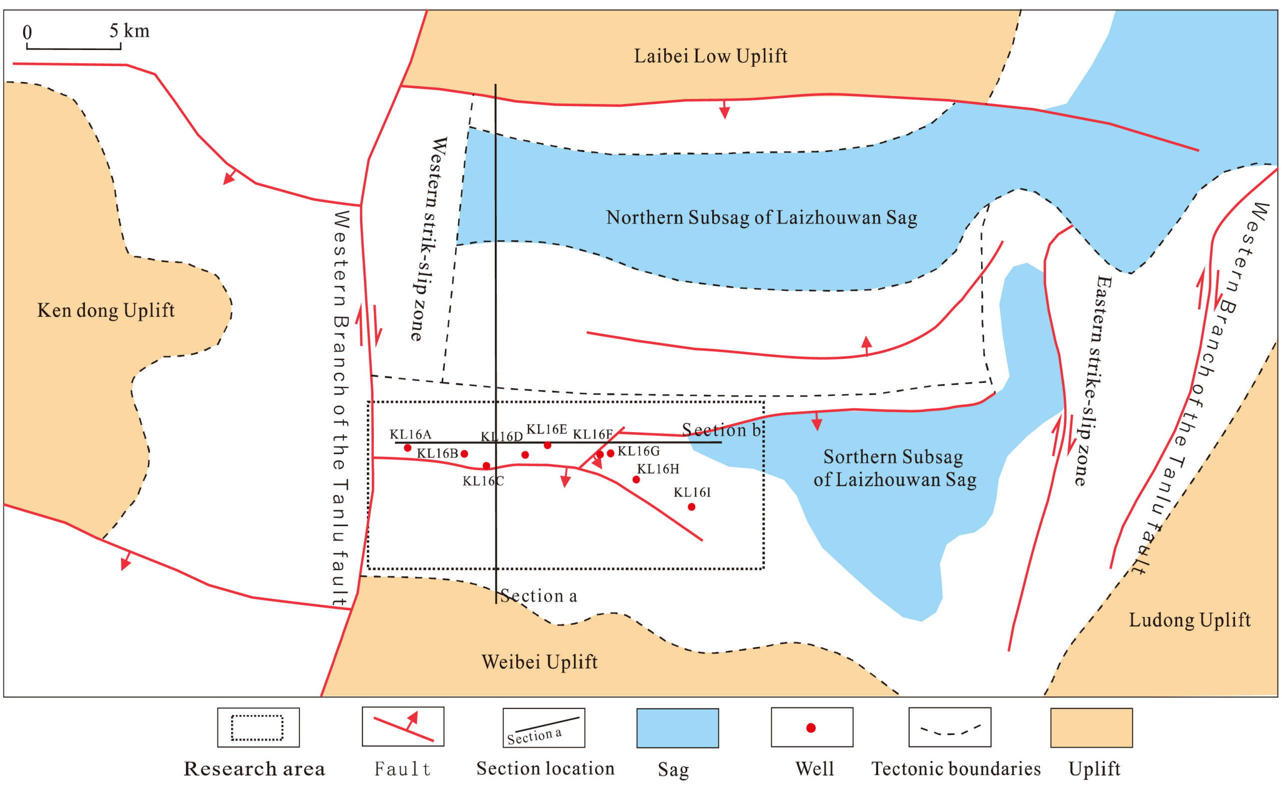

Figure 1. Structural outline of Laizhou bay area.

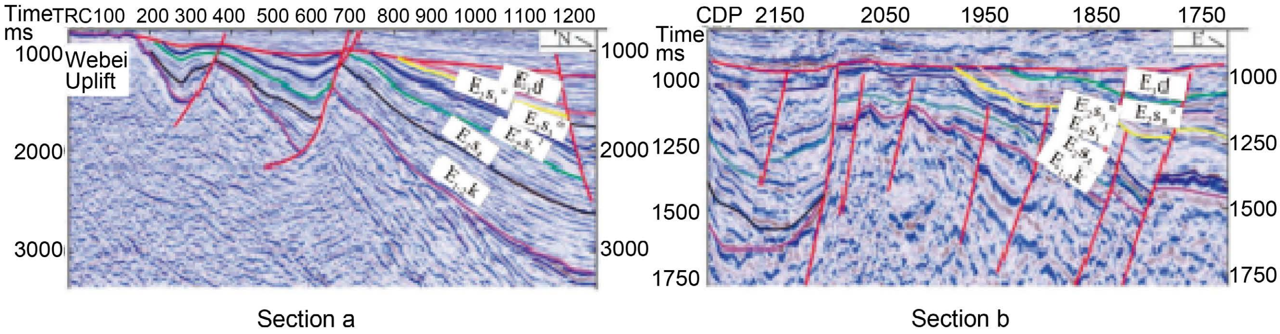

Figure 2. Typical seismic interpretation profile of KL16 area in Laizhouwan sag.

lithology is mainly fine sandstone, micrite limestone and dolomite; The thickness of single layer of delta sedimentary sandstone is generally between 10.5 and 17.6 m, and the lithology is mainly medium fine sandstone and pebbly fine sandstone (Figure 3).

The special structure, sedimentary background and reservoir rock type of KL16 oilfield make it difficult to understand the reservoir distribution law of lower Es3 member, which restricts the exploration and development process of this area.

3. Restoration of Paleogeomorphology in the Lower Section of Sha 3

At present, the commonly used methods of ancient landform restoration mainly include sedimentology analysis, sequence stratigraphy analysis, stratum thickness method, impression method, back stripping and filling and leveling [12]. Structural analysis shows that KL16 oilfield is located at the high part of the gentle slope belt at the edge of Laizhouwan depression basin, and has experienced the early fault depression from Kongdian Formation (EK) to the third member of Shahejie Formation (Es3), the middle strike slip and late activation stage from the first and second members of Shahejie Formation (Es1 + 2) to Dongying Formation (ED) (since Neogene) [13]. According to the characteristics of complex tectonic evolution in the study area, the combination of structural recovery and stratigraphic recovery is targeted to restore the ancient landform. In the process of restoration, the key technologies of denudation recovery, fault and fold removal and compaction correction are mainly used.

3.1. Denudation Recovery

The restoration of denudation amount is an important link in the restoration of ancient landform. Only the thickness of the remaining strata and the denuded strata can show the ancient thickness of the strata, and the denuded thickness is also the premise of compaction recovery.

At present, there are many methods to calculate the denudation amount [14] [15], and no one can accurately calculate the denudation amount. If the data of the studied area is well based, more than two methods can be comprehensively

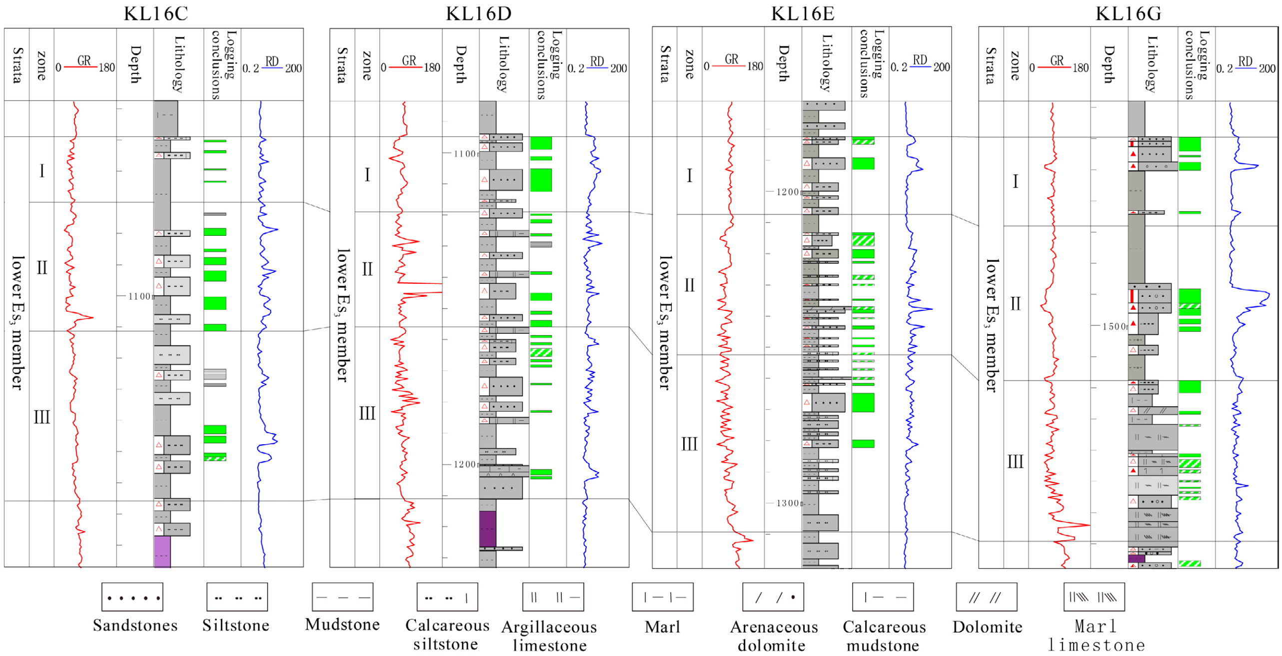

Figure 3. Stratigraphic correlation of lower member of Es3 in KL16 oilfield.

used to calculate the denudation thickness according to its characteristics, so as to obtain more reliable data. Due to the local denudation of the inner layer in the depression of the slope belt in the study area, and the lack of obvious stratum cutting phenomenon due to the influence of deep and large faults, the trend thickness method can not be used for recovery, and only the mudstone acoustic time difference method can be used for point recovery; However, there is obvious formation cutting at the height of the upward bulge of the slope belt, and there is a lack of drilling data at the same time, so the formation trend thickness method can be used for line recovery. Therefore, based on the analysis of regional geological background and structural evolution, the combination of acoustic time difference method and trend thickness method is mainly used to recover the denudation amount of the stratum. The calculation shows that the denudation intensity of the lower sub section of the third member of the Shahejie Formation in the lainan slope belt is large, of which the average denudation amount in the west is about 1200 m, and the maximum denudation amount is 1300 m, and the denudation degree in the East is small [11].

3.2. De Faulting and De Folding

In the process of paleostructure restoration, it is necessary to eliminate the influence of structural deformation caused by folds and faults on the strata. The oblique shear method is the most commonly used method for fault and fold removal [16]. This algorithm is applicable to KL16 area, which is dominated by extensional tectonic movement.

In this paper, several typical seismic lines that can reflect the geological characteristics of the oilfield are selected. First, they are successively imported into the recovery software, and the top and bottom interfaces and main faults of the lower member of Sha 3 are explained in the software; Secondly, in the recovery software, the interpreted survey line is processed to remove the fault offset, which should ensure the reliability of the obtained results; Finally, the three-dimensional coordinate data of each point at the bottom boundary of the lower section of Sha 3 are obtained by flattening and de folding the top surface of the lower section of Sha 3.

Through structural evolution analysis and geological software, the residual thickness map after structural correction is calculated from the data obtained by the recovery software, and the paleogeomorphology of the study area is preliminarily displayed (**Figure 4**).

3.3. De Compaction Correction

The de compaction process is mainly to remove the impact of compaction caused by different depths and lithological changes in different parts of the formation. For sand mudstone formation, with the increase of burial depth, the porosity decreases correspondingly, resulting in the formation thickness becoming thinner. Therefore, the de compaction correction is actually the recovery correction of formation porosity.

Previous research results suggest that the formation porosity decreases regularly with the increase of depth [17]. According to the measured porosity data of exploratory wells in KL16 oilfield, the mathematical quantitative relationship between porosity and depth of mudstone, sandstone + migmatite in this area is established (**Figure 5** and **Figure 6**).

At the same time, the integral equation of rock skeleton [18] is used to analyze the thickness of the skeleton before restoration and the thickness of the skeleton before restoration. According to the calculation, the corrected compaction rate in the study area is 1.2 - 1.4 (**Table 1**).

The paleogeomorphology of the lower member of the third member of the Shahejie Formation in the study area has been finely restored through denudation recovery, fault and fold removal and compaction correction. According to

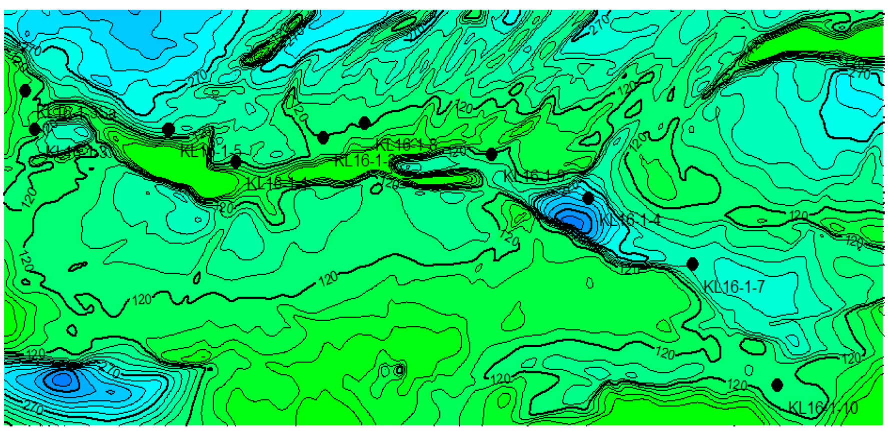

Figure 4. Residual thickness diagram. (Before correction)

the difference of palaeogeomorphology, four geomorphic types are identified: bulge, slope, platform and depression (Figure 7). During the sedimentation

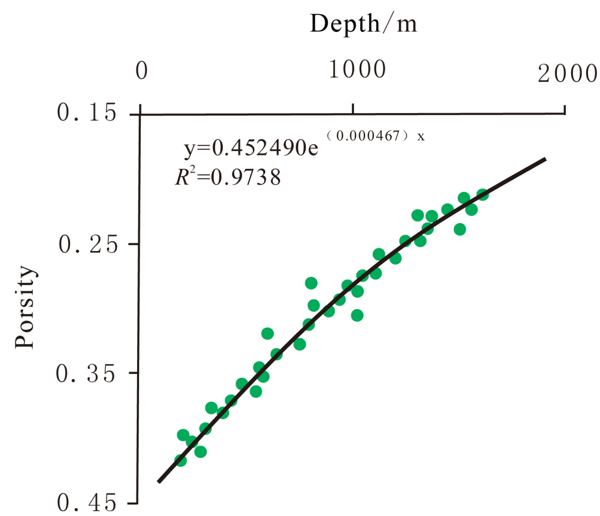

Figure 5. Porosity depth relationship of sandstone + migmatite.

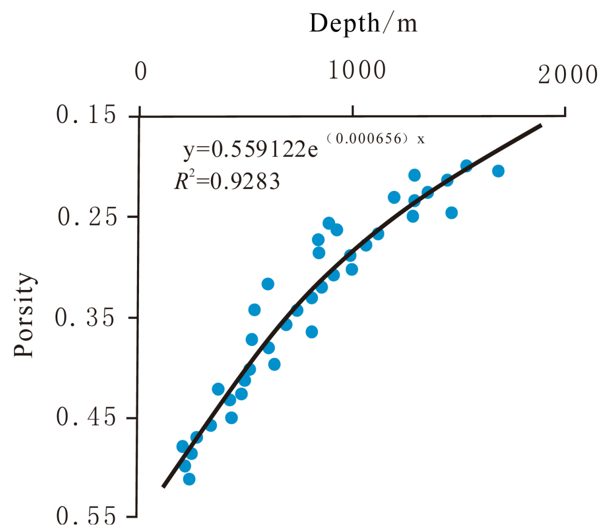

Figure 6. Porosity depth relationship of mudstone.

Table 1. Compaction rate data of KL16 Oilfield.

Well number	Burial depth (m)	Mud thickness (m)	Mudstone compaction coefficient	Mudstone porosity	Burial depth (m)	Mud thickness (m)	Compaction coefficient of sandstone	Sandstone porosity	Compaction rate
KL16C	1057.0	87.7	0.000617	0.512	1057.0	29.9	0.000431	0.421	1.24
KL16D	1117.0	102.0	0.000621	0.523	1117.0	42.0	0.000435	0.428	1.25
KL16A	1116.0	79.8	0.000621	0.523	1117.0	12.2	0.000435	0.428	1.25
KL16E	1223.6	93.9	0.000632	0.536	1223.6	33.1	0.000441	0.435	1.31
KL16G	1504.0	97.2	0.000656	0.5591	1504.0	32.9	0.000467	0.4525	1.36

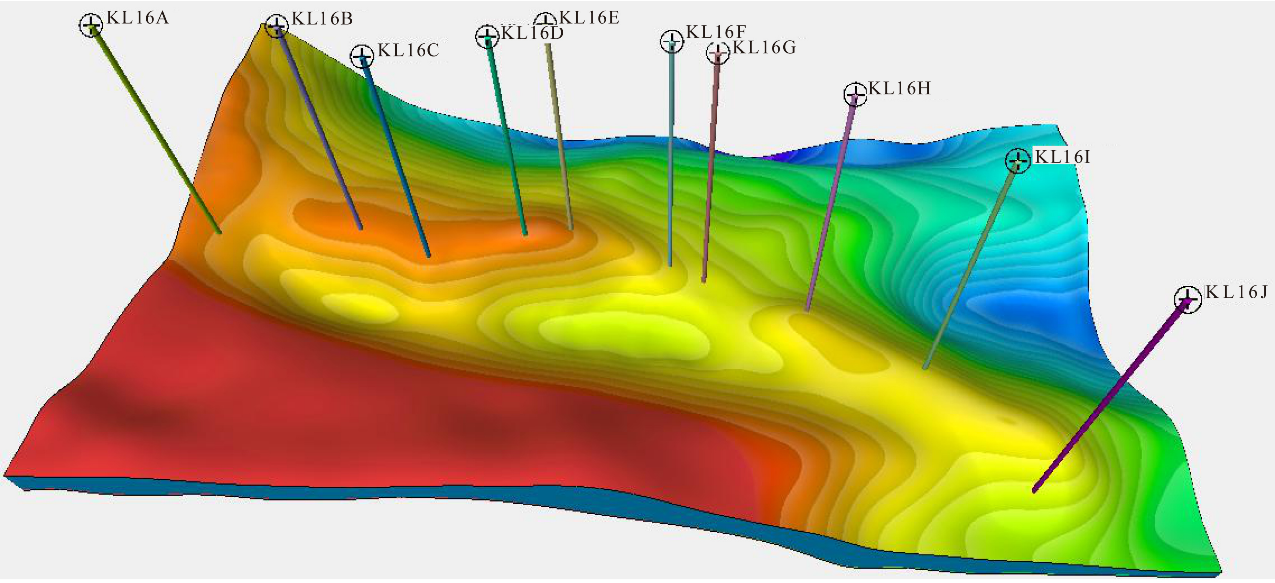

Figure 7. Paleogeomorphology of the lower member of Shahejie formation during the sedimentation period.

period of the lower member of Sha3 formation, due to the influence of tectonic movement, the paleogeomorphology in this area has obvious differences in the east-west direction and the north-south direction. The West and south of the study area mainly develop bulges and slope landforms (the West bulge is outside the work area), the central part develops platform landforms, and the north and northeast parts develop depression landforms.

4. Control of Paleogeomorphology on Sedimentary System and Sedimentary Model

The controlling effect of paleogeomorphology on sedimentation is shown in that different paleogeomorphic units play different roles in the process of sediment transportation and sedimentation from source to sink: the uplift area or paleouplift is generally a long-term denudation landform, providing material source; In the early stage of sedimentation, the ancient gullies or channels and ancient slopes were mainly used as channels for transporting material sources, and in the late stage, they were filled by sedimentation; The ancient fault slope and underwater low uplift play a dispersive role on the material source. The depression or depression area is the sediment unloading area. The depression edge and shallow depression area are mainly various fan bodies, deltas and shore shallow lakes, and the deep depression area is mostly semi lacustrine sediments [12]. The sedimentary system of the lower Es3 member of the oilfield is studied by using core, thin section, seismic and logging data. It is considered that the sedimentary facies of the lower Es3 member mainly includes Braided River Delta, shore shallow lake mixed beach bar and fan delta (**Figure 8**). The superimposition diagram of paleogeomorphology and sedimentary system shows that the paleogeomorphology has an obvious control over the distribution of sedimentary system in the lower sub member of Sha 3 (**Figure 9**).

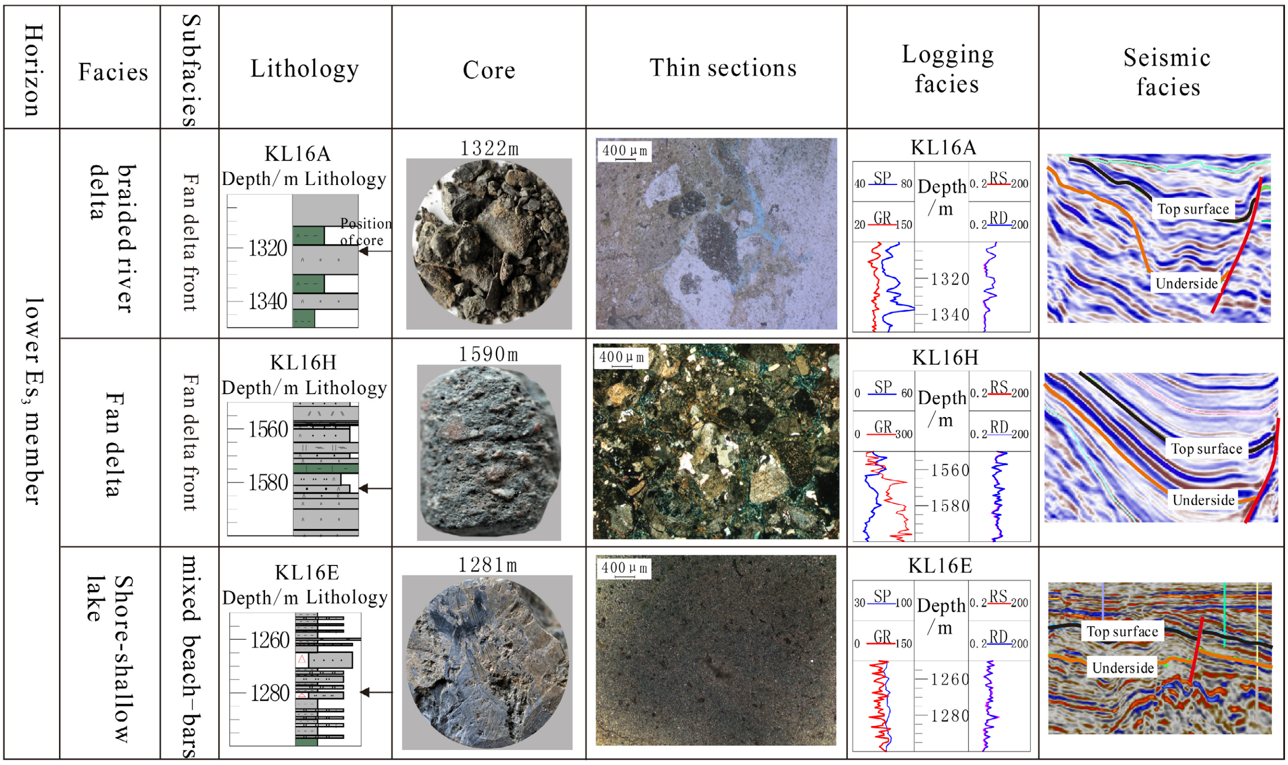

Figure 8. Development characteristics of different sedimentary systems in the lower member of Es3.

4.1. Western Braided River Delta Sedimentary System

Braided river delta is mainly developed in the western slope belt. The main structure of Kendong uplift is distributed outside the study area, and the provenance is far away from the study area. During the sedimentation period of the lower member of the third member of the Shahejie formation, the provenance of Kendong uplift was transported to the depression area of the study area through the large gully on the slope background, forming the Western Braided River Delta [19]. At present, only braided river delta front sediments are found in the study area (**Figure 9**). The East-West seismic interpretation section has the characteristics of wedge-shaped progradation reflection structure. Among the drilled wells in the oilfield, only KL16A have encountered braided river delta front subfacies. The lithology is mainly greyish green tuffaceous sandstone conglomerate, gray fine sandstone and greyish green mudstone interbedding. The rock particles are sub angular and sub rounded, and a small number of neutral extrusive rock blocks are seen. The logging curve of the glutenite section is in a rhythmic cycle with a bell type characteristic. The well logging curve of the interbedded section of fine sandstone and mudstone presents funnel-shaped reverse cycle with finger like characteristics (**Figure 8**).

4.2. Southern Fan Delta Sedimentary System

Fan delta sediments are mainly developed in the south of the study area. Due to the gentle slope of the southern slope zone, the energy of the river on the alluvial

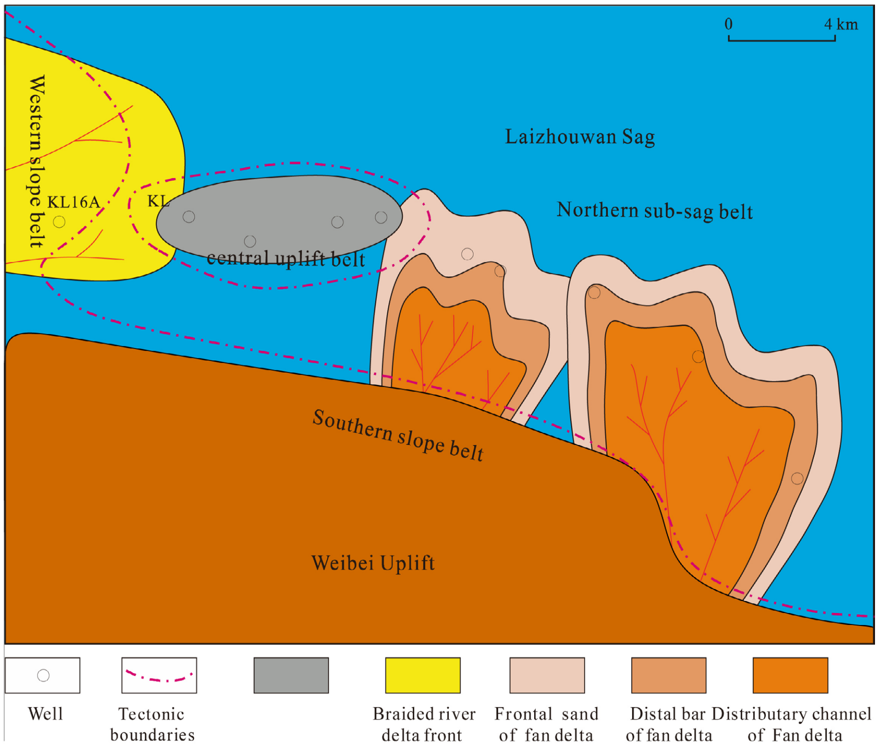

Figure 9. Superimposition of sedimentary system distribution and paleogeomorphic units in the lower member of Es3.

fan will soon disappear after entering the lake, and the sediment carried by it will be rapidly deposited, thus forming a narrow coarse clastic belt [20]. The Weibei uplift in the south of the study area is the main provenance area, the Ludong uplift in the southeast is the secondary provenance area, the large gully between the Weibei uplift and the Ludong uplift, and some small gullies are also developed in the southern slope belt. The alluvial fan in the provenance area advances along the gully, forming a fan delta at the depression edge in the southeast of the study area (**Figure 9**). The seismic interpretation section passing through the north-south direction shows wedge-shaped progradation reflection characteristics. KL16H encountered the far sand bar of subfacies in the front of the southern fan delta. The main lithology is gray sand conglomerate, and greyish green tuff is developed. The core and thin section data show that the rock particles are sub angular to sub circular, with poor sorting. The logging curve of the gravel section is in a rhythmic cycle, and the curve shape is mainly bell shaped (**Figure 8**).

4.3. Central Littoral Shallow Lake Sedimentary System

Shore shallow lake sediments are mainly developed in the middle of the study area. During the sedimentation period of the lower member of Sha 3, the well areas KL16C, KL16D and KL16E in the middle of the study area are platform paleogeomorphology under the depression background. They are less affected by the material sources of Kendong uplift on the west side and Weibei uplift on the south side, and the littoral shallow lake mixed rock deposits are developed

(**Figure 9**). Sheet like, parallel and strong reflection characteristics can be seen in the seismic profile of the lower member of Sha 3, with high amplitude, good continuity and medium to low frequency. In KL16C, KL16D and KL16E in the middle, the reservoir lithology is the interbedding of gray (dolomitic) sandstone, sandy limestone (dolomite) and mudstone and marl. Among them, the mineral composition of sandstone is mainly quartz, feldspar and rock debris. The clastic particles are evenly distributed, and the interstitial materials are argillaceous and micrite dolomite; Dolomite or limestone, argillaceous texture, mainly composed of argillaceous dolomite and argillaceous calcite, and a small amount of argillaceous and terrigenous debris can be seen. The logging curve has low gamma characteristics and the curve has zigzag characteristics (**Figure 8**).

4.4. Evolution of Sedimentary Model

Through comprehensive analysis of sedimentary system, surrounding material source and drilling data, a sedimentary model jointly controlled by double slope and platform between depressions is established (**Figure 10**). Clastic rock deposits are developed on both slopes and mixed rock deposits are developed on the platform within the depression.

In the study area, the material supply of the lower SHA3 member is sufficient, the sediments are rapidly deposited, the sedimentary area is increasing, and the lake shoreline is gradually shrinking. In the early stage of the lower member of Shahejie formation, braided river delta deposits were developed in well KL16A under the control of Kendong uplift source area and western slope zone; Controlled by the inner platform of the depression, mixed beach bar deposits are developed in well areas KL16C, KL16D and KL16E; Controlled by Weibei uplift, well blocks KL16H, KL16I and KL16J are located in weathering and denudation area. In the middle stage of sedimentation, braided river delta deposits developed in well KL16A of the western slope area; In addition to being controlled by the platform, well KL16E is also affected by the provenance of Weibei uplift, with the increase of terrigenous clasts and the decrease of carbonate rock content; Controlled by the provenance of Weibei uplift and the southern slope zone, fan delta deposits began to develop in well areas KL16H, KL16I and KL16J. In

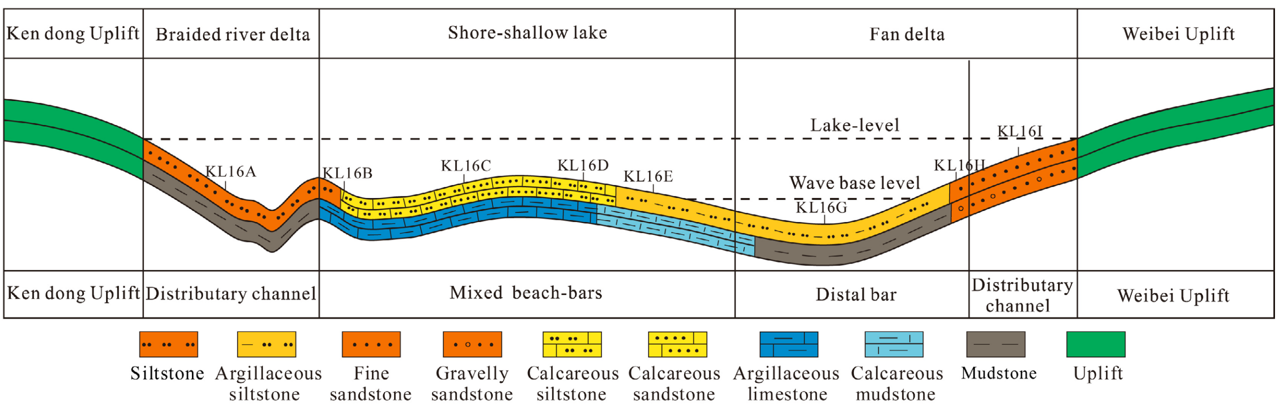

Figure 10. Sedimentary model of clastic rock + migmatite in the middle stage of lower member of Es3.

the late stage of sedimentation, the supply of material source further increased, the sedimentary area gradually increased, the range of lake basin gradually decreased, and the distribution range of platform further decreased. Mixed beach bar deposits are only distributed near well KL16C. Further promoted by the material source of Weibei uplift in the south, fan delta deposits are developed in well KL16D, KL16E, KL16H, KL16I and KL16J; The distribution range of braided river delta deposits in the western slope zone is gradually increasing.

5. Favorable Reservoir Prediction Based on Facies Belt

The sedimentary system of KL16 oilfield is diverse and the lithology is complex. At the same time, the signal-to-noise ratio of seismic data is low, the main frequency is about 12 Hz, the vertical resolution is 40 - 60 m, and the overall thickness of single sand body is less than 2 m. The existing seismic resolution can not identify single sand body, and the reservoir plane development law is unclear. At present, it is difficult to predict the Paleogene thin interbedded reservoir due to the problems of vertical resolution of seismic data and few well data. The conventional method is to establish a forward modeling model and obtain forward modeling records according to the formation structure and petrophysical parameters of the exploratory well. Various seismic attributes are extracted from the forward modeling records and intersected with the well point sand ground ratio or reservoir thickness. The attribute with high correlation is preferred as the sensitive seismic attribute; It provides theoretical guidance for extracting seismic attributes from actual seismic data. There is uncertainty in predicting thin interbedded reservoirs in this way. First, the model is too simple to reflect the actual geological conditions underground; Second, there are few well data and the obtained correlation is unreliable.

In this paper, the principal component coupled reservoir prediction technology based on sedimentary facies belt constraint is used to predict the planar distribution of reservoirs. The first step is to carry out waveform clustering analysis. Waveform clustering uses the waveform differences caused by the lithology or lithofacies of underground strata to cluster different types of geological bodies [21]. On the basis of petrophysical analysis and research, this paper carries out neural network clustering analysis on seismic channel waveforms, and selects four clustering numbers to obtain four seismic facies with different colors. Among them, orange indicates the mixed rock development area, and other colors represent the mudstone development area. The waveform clustering results are consistent with the drilling conditions of exploration wells. Under the constraints of sedimentary systems, the ancient landform According to waveform classification and actual drilling, the sedimentary facies belt is finely determined. The main sedimentary facies are divided into delta front subfacies and shore shallow lake mixed beach bar facies (**Figure 11**); The second step is to make synthetic seismic records of exploration wells, which are the most objective forward simulation of underground geological conditions [22]. The seismic attributes are extracted from the synthetic seismic record set and cross analyzed with the reservoir thickness, and the seismic attributes with high correlation are selected as the suspected sensitive seismic attributes of the reservoir thickness. The waveform clustering analysis results and the suspected thickness sensitive seismic attributes are taken as the input of the principal component analysis, and the first principal component is taken as the output. The first principal component retains the most common features of the original input, has high correlation with reservoir thickness, and realizes reservoir prediction based on facies control (Figure 12). According to reservoir prediction, sedimentary microfacies and comprehensive evaluation of lithology, physical properties and productivity of development wells, it is considered that mixed facies cloud and lime beach bar are high-quality reservoir development areas.

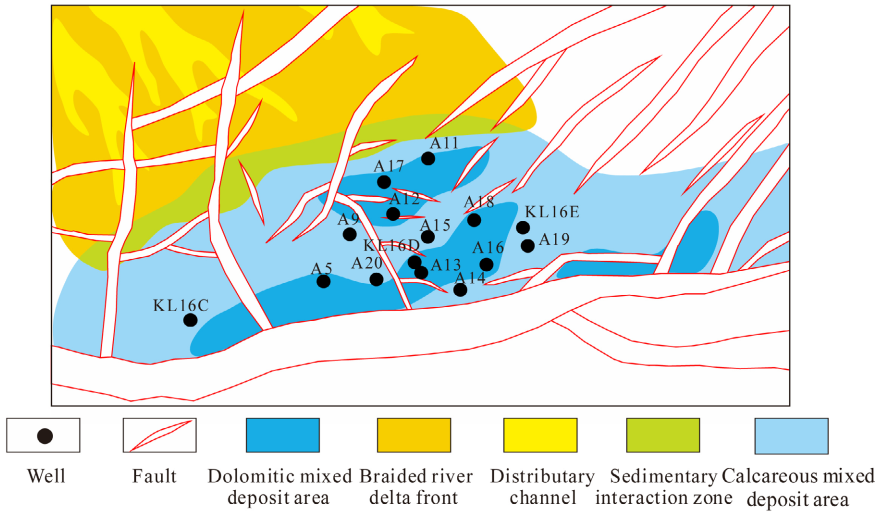

Figure 11. Sedimentary facies diagram of the lower member of Sha 3 in the development well area.

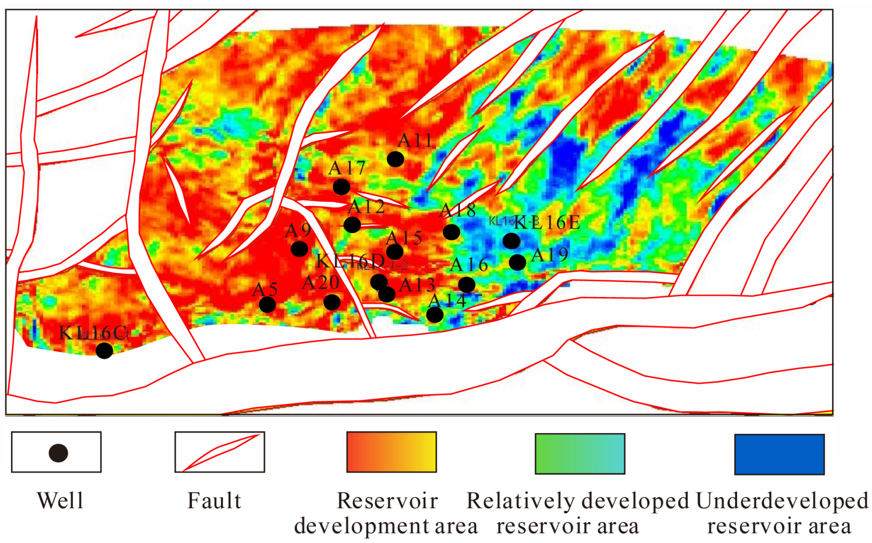

Figure 12. Seismic reservoir prediction diagram of the first principal component.

6. Application Effect

Based on the fine geological analysis of the reservoir in the lower member of the third member of the Shahejie Formation in the study area and the prediction of the facies controlled dominant reservoir, the well location of the first batch of development wells in the oilfield was optimized, and good application results were achieved after implementation. After drilling of the development well, it is confirmed that the reservoir genesis and distribution are basically consistent with the pre drilling understanding; The predicted average reservoir thickness of a single well before drilling is 28 m, and the actual average reservoir thickness of a single well after drilling is 31 m, and the reservoir penetration rate is increased by 10%; The predicted initial production capacity before drilling is 1056 m^3/D, and the actual flowback after drilling is 1219 m^3/D, which is 1.2 times the design capacity; The rolling evaluation added 5 million cubic meters of proved reserves.

7. Conclusion

1) The combination of structural restoration and stratigraphic restoration is comprehensively used to restore the paleogeomorphology of the lower member of the third member of the Shahejie Formation in KL16 oilfield, and four geomorphic types are identified: uplift, slope, uplift and depression. The West and south of the study area mainly develop bulge and slope landforms (the Western bulge landforms are outside the study area), the central part develops bulge landforms, and the north and northeast parts develop depression landforms.

2) Controlled by the ancient landform, the oilfield mainly develops three different sedimentary environments: Braided River Delta in the west, shore shallow lake mixed beach bar in the middle and fan delta in the south.

3) Based on the research of principal component coupling reservoir prediction technology constrained by sedimentary facies belt, it is clear that mixed facies cloud and gray beach bar are high-quality reservoir development facies belt. The results are applied to optimize the well location of development wells. After drilling, it is confirmed that the single well reservoir penetration rate is increased by 10%, and the actual production capacity is 1.2 times of the design. The rolling evaluation adds 5 million tons of proven geological reserves of crude oil.

4) The development practice shows that the study of micro paleogeomorphology in the study area plays an important role in the study of sedimentary microfacies and the distribution of mixed rocks. At the same time, the principal component coupling reservoir prediction technology based on the constraint of sedimentary facies is feasible in the prediction of mixed rock reservoirs in the Bohai Sea, which has a good guiding significance for the exploration and development of mixed rocks in the Bohai Sea.

Conflicts of Interest

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

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