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Paleogeomorphic Influence on Facies Characteristics and Reservoir Prediction in Lacustrine Basin

—By Taking Cretaceous Reservoirs in the Western Slope of SL Basin, China as an Example

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Abstract

The West Slope of SL Basin, China, mainly targets on lithologic reservoirs for oil and gas. The paleogeomorphology and provenance direction analysis has great significance for predicting the type and distribution of sand body. According to the analysis of well logging, core and seismic data, braided delta and gravity sediment mainly develop in the study area. A backs tripping method is used to reconstruct the topography of Qingshankou to Yaojia Formation, Cretaceous. The West Slope is mainly controlled by two slope belts in Qingshankou Formation, with the width of upper slope 12 - 18 km and the gradient 0.7 - 0.8 degrees, the width of lower slope 13 - 15 km and the gradient 1.0 degrees. The West Slope is controlled by a single slope belt in Yaojia Formation, with the lower slope width of 13 - 16 km and the gradient 0.4 degrees. The relationship between the slope belt, provenance direction and sand body distribution is analyzed, and result shows that the combination of upper and lower slope controls the distribution of reservoir types, and the provenance supply rate controls the scale of sand body. The gravity flow develops when the provenance direction is parallel to slope direction, and the slope becomes transporting channel in vertical to provenance direction. The paleogeomorphology, lake level and provenance direction are the main control factors of sand body in West Slope.

Keywords

SL Basin, Paleogeomorphology, Slope Belt, Sedimentary Type

1. Introduction

The Western Slope of SL Basin is a large monocline with eastward inclination, and the oil and gas exploration target is mainly on lithologic reservoir. Oil was successively found in Fulalji and Taikang Uplift in the Western Slope, indicating that the Western Slope Area had favorable oil and gas exploration prospect [1] [2]. The Qingshankou Formation and Yaojia Formation is characterized by strong tectonic activity and multiple sedimentation provenance. The paleogeomorphology and source-to-sink system controlled the transmission, distribution and sedimentation of the sand bodies, and was of great significance for the prediction of sand body distribution [3] [4] [5] [6]. Xin *et al.* rebuilt the thickness map of the Cretaceous strata of SL Basin by seismic analysis, and identified the evolution of the slope qualitatively [7]. Xin *et al.* analyzed the characteristics of slope belt and its control on reservoir distribution by means of well logging-seismic analysis, stratigraphic correlation and sedimentary facies analysis [8]. Guo *et al.* studied the control of slope belt on sequence, and reservoir distribution characteristics by using high resolution 3-D seismic data [9].

However, the accuracy of the previous qualitative restoration of the paleogeomorphology cannot meet the need of oil exploitation, and slop factor is not enough for prediction of oil exploration. Based on the study of core, well logging and seismic data, the sedimentary types are analyzed in this paper. A backstripping method is used to restore the terrain of Qingshankou to Yaojia Formation, and the topographical features of Qingshankou to Yaojia Formation in the West Slope are quantitatively recognized. The relation between slope belt, provenance direction and sedimentary system distribution is analyzed, and the reservoir development pattern and main controlling factors in the lacustrine basin are studied. It provides a reference for further evaluation of the exploration potential of the Western Slope.

2. Geological Setting

The Western Slope of SL Basin is located in the west of Qijia-Gulong Depression, west to the basin boundary, and north to Baoshan County. The study area is about 24,000 km^2 (**Figure 1**, left), including the west of Qijia-Gulong Depression, Longhupao-Daan Terrace, Taikang Uplift Belt, and Western uplift. The strata of the study area includes Quantou, Qingshankou, Yaojia, Nenjiang, Sifangtai and Mingshui Formations, Paleogene, Neogene and Quaternary (From down to up) [10]. At the early stage of the Qingshankou Formation, SL Basin underwent large-scale transgression, formed a deep depressed basin with wide lake area. At the end of the Qingshankou Formation an overall tectonic uplift occurred, and the global sea level dropped significantly at the same time, causing large-scale lake regression in SL Basin. As a result, the lake area shranks greatly (**Figure 1**, right).

3. Sedimentary Types and Distribution

The depressed basin in Qingshankou Formation is mainly affected by the North, Qiqihar and Yingtai provenance. The North provenance is the strongest and controls the sediments in the most areas [11]. The topography of Yaojia

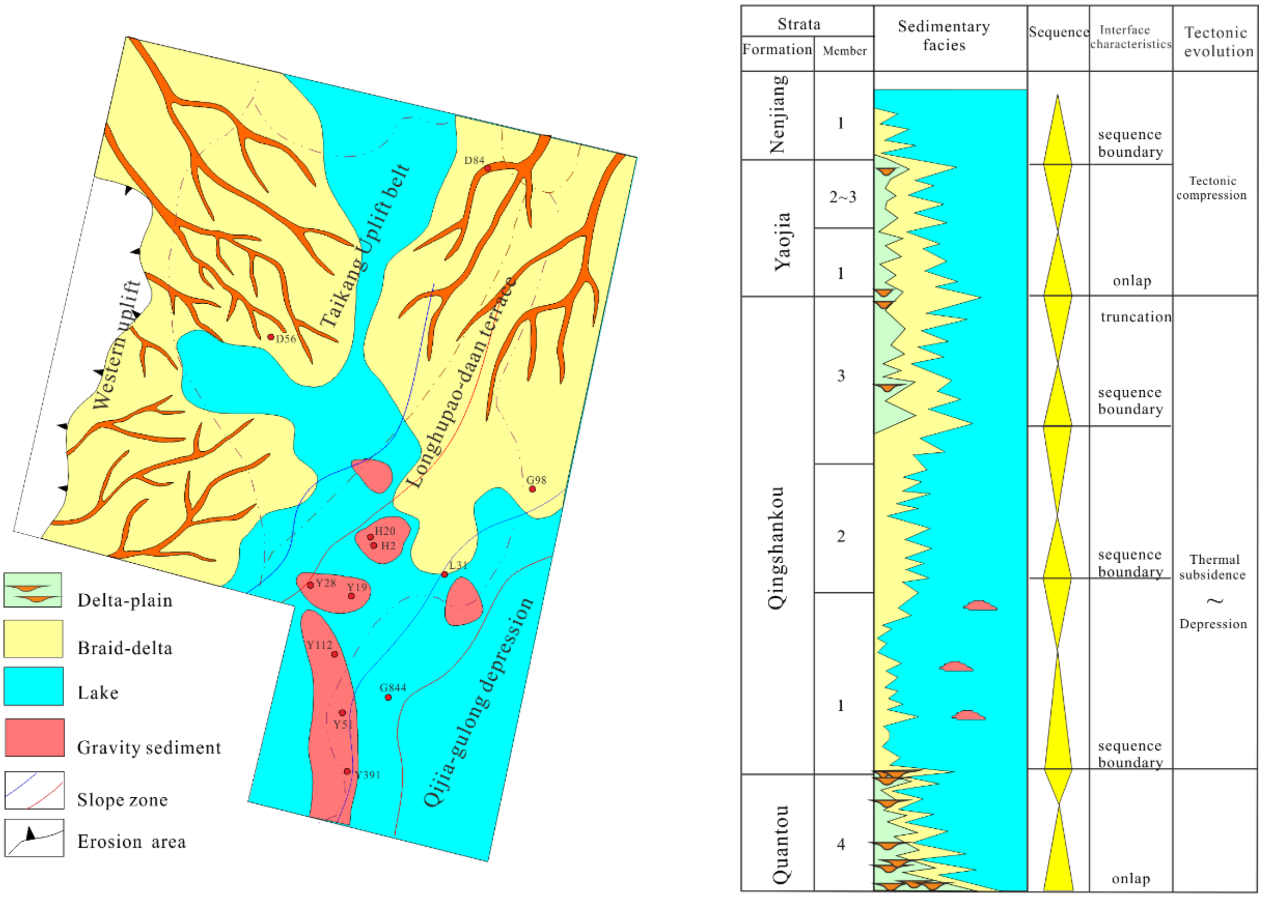


Figure 1. The sedimentary facies map in 1st Member of Qingshankou Formation in the West Slope (left) and the stratigraphic chart of Qingshankou to Yaojia Formation (right).

Formation is shallower, the deltaic lobes are superimposed and affected by multi-provenance. And the provenance moves from the west to east clockwise. Eleven wells in the Western Slope Area are selected for core observation. Combined with the gamma ray and density logging curves, it is found that braided-delta, gravity sediments, coastal and shallow lake sediments mainly develop from Qingshankou to Yaojia Formation in the Western Slope, and the main reservoirs are delta front sand bodies, biotic bar and gravity sediments.

The gravity sediments are mainly developed in the first and second Member of the Qingshankou Formation. The gravity flow deposition is mixed with the dark mudstone and prodelta. The sandy clastic deposits are mainly composed of fine and siltstone. Sliding deformation bedding and blocky bedding are commonly developed [12]. The bottom of sandy clastic deposits are in contact with the dark mudstone (**Figure 2(a)**). The turbidity sediment is composed of clay and medium to fine size sediments, mainly derived from the dilution of detrital flows [13], mostly siltstone and silty mudstone, which are in contact with the underlying dark mudstone. The Bouma sequence, liquefaction structure, massive bedding, horizontal bedding and corrugated bedding are commonly found in turbidity sediments (**Figure 2(b)**). The delta front is mainly composed of underwater distributary channel, mouth bar and sheet sand. The underwater distributary channel is mainly composed of medium and fine sandstones and siltstones, which are well sorted and usually show rhythm of upward thinning. Large cross and parallel beddings are developed (Figure 2(c) and Figure 2(g)), and scour surface is often developed on the bottom of river channel. The mouth bar is mainly composed of fine sandstone and siltstone with granule medium to good sorted, ripple cross and small cross beddings. The particles are in an upwardly coarse rhythm, and biotic bar is developed on the top of the mouth bar (Figure 2(d) and Figure 2(f)). The sheet sands are thin layers of siltstone and mud siltstone, and ripple bedding, horizontal bedding, are commonly found. There are lots of plankton and carbon debris along the layers, with biological perturbation structure and scattered distribution of biological fossils (Figure 2(e)).

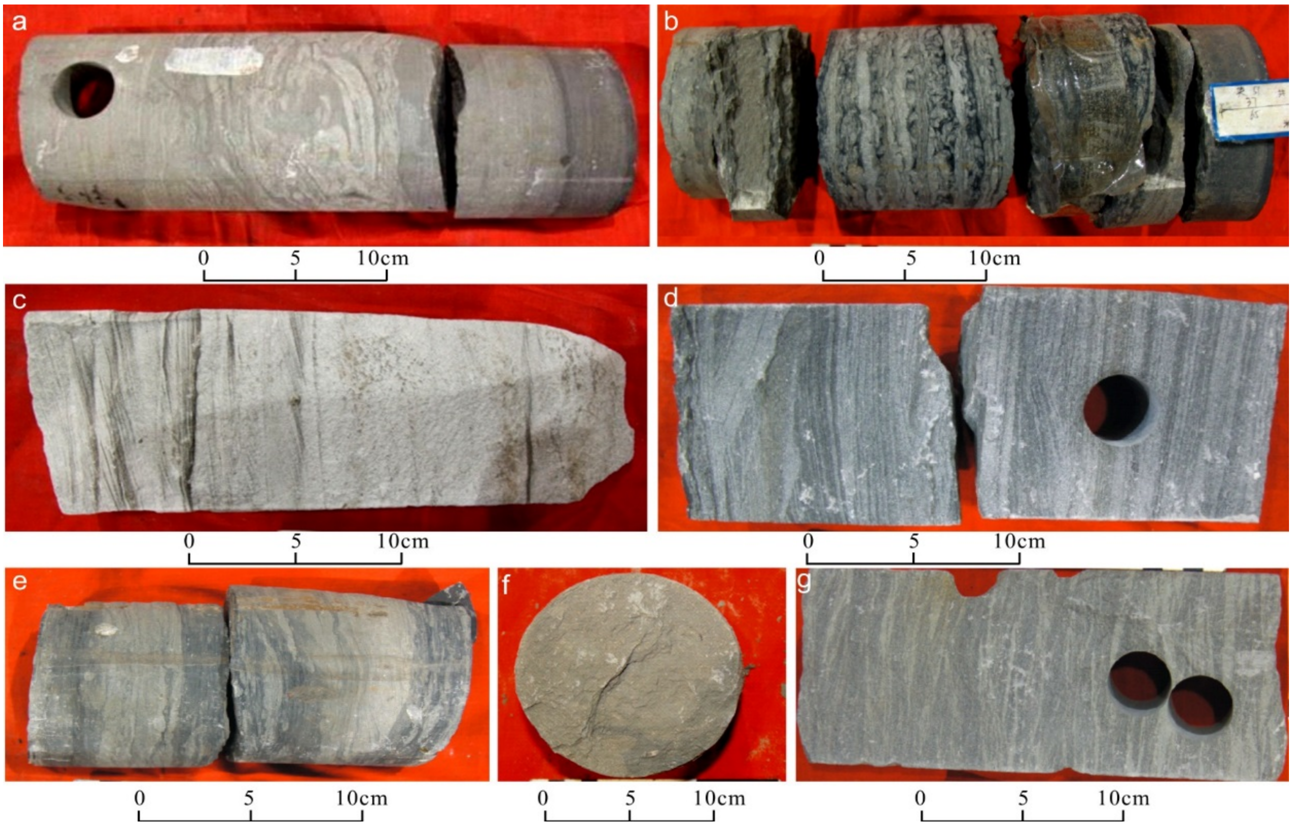


Figure 2. The sedimentary characteristics of Qingshankou to Yaojia Formation in West Slope Area. (a) Siltstone, deformation bedding, gravity flow deposition, First Member of Qingshankou Formation, Well Y51; (b) Thin interlayer of sandy mudstone, liquefaction structure, Bouma sequence, gravity flow deposition, First Member of Qingshankou Formation, Well Y51; (c) Fine sandstone, one-way flow bedding, underwater distributary channel, First Member of Qingshankou Formation, Well D84; (d) Fine sandstone, parallel bedding, two-way flow bedding, mouth bar, Yaojia Formation, Well L31; (e) Deformation bedding, sheet sand, Second Member of Qingshankou Formation, Well G98; (f) Biotic mudstone, mouth bar, Yaojia Formation, Well D56; (g) Small trough cross-bedding, underwater distributary channel, Yaojia Formation, Well G844.

4. Paleogeomorphologic Reconstruction

The previous study mainly focuses on the genesis and evolution of the slope belt in the Western Slope, where the thickness map of present strata is mainly used to reflect the variation of geomorphology [14]. However, the present strata are incomplete after subsidence compaction, subsequent erosion, and tectonic compression, which are quite different from the strata of the initial deposition [15]. This study conducts series work on the restoration of eroded strata, de-compaction correction and palaeowater-depth correction after interpretation of the strata. As a result, the original strata thickness is quantitatively restored.

4.1. Recovery of Eroded Strata Thickness

Eroded strata recovery is of great significance for the restoration of paleogeomorphology. The ancient thickness can be truly shown only when the eroded thickness is added to the strata [16]. If there are regular changes of strata thickness in seismic cross section, the thickness of the eroded strata can be estimated by interpolating or extrapolating the uneroded strata. At the end of the Qingshankou Formation the tectonic compression causes the western side of the SL Basin to uplift. As a result the Third Member of the Qingshankou Formation is eroded. The paleogeomorphology is obviously eroded, thus, the trend extension method is adopted to restore the strata.

4.2. De-Compaction Correction

Porosity varies regularly with the changes of burial depth caused by effective stress in the process of subsidence compaction [17]. This study uses an exponent model including porosity and depth data to formulize the porosity (ϕ)—buried depth (H) curve of different lithologies. The ϕ-H equation of the mudstone or sandstone is:

$$\text{Sandstone:}\quad \phi = 0.4048\mathrm{e}^{-0.000429H} \tag{1}$$

$$\text{Mudstone:}\quad \phi = 0.6571\mathrm{e}^{-0.000571H} \tag{2}$$

The original strata thickness can be deduced by the skeleton integral formula on the premise that the sand skeleton remains unchanged [18].

$$T = H_2 - H_1 - \frac{\phi_0}{c}\left(\mathrm{e}^{-cH_1} - \mathrm{e}^{-cH_2}\right) + \frac{\phi_0}{c}\left(1 - \mathrm{e}^{-cH}\right) \tag{3}$$

where ϕ_0 is the porosity is the depositional porosity and c is the compaction coefficient. Assuming the burial depth of the strata is H_1 at its top and H_2 at its bottom, so that as the deposit flattens to its initial depositional surface, the original thickness of the strata is T.

Data from about 100 wells is used to restore the original thickness of Qingshankou to Yaojia Formation of the West Slope. The compaction rate is obtained by the ratio of restored thickness to original thickness. And the result shows that the compaction rate varies in the range of 1.19 - 2.00.

4.3. Correction of Palaeo-Water Depth

As strata thickness was restored, the palaeo-water depth correction is carried out through the analysis of sedimentary structure, biological fossils and lithofacies [19] [20] [21]. For instance, water depth of the hummocky cross-bedding or

Bouma Sequence development is generally deeper than 30 m, and water depth of the parallel bedding or wave bedding is developed at 5 - 20 m, while the large cross-bedding is developed at 1 - 5 m.

5. The Distribution of Sedimentary System under the Control of Paleogeomorphology

The paleogeomorphological features show that the structural unit of the Western Slope is dominated by slope belts, and the accommodating space near the slope-break zones is varied, which often leads to the change of sedimentary facies or sedimentary thickness. On the strata thickness isopach map, the contour line is dense at the slope, and the strata thickness increases sharply from the slope zone to the slope toe.

5.1. Identification of Slope Belts and Their Distribution Features

Early in the Qingshankou Formation, the West Slope Area is controlled by both upper and lower slope belts. The upper slope belt has a southwest-northeast trend with about 12 - 18 km in width and slope gradient ranges from 0.7˚ to 0.8˚. The lower slope belt has a southwest-northeast trend with about 13 - 15 km in width and slope gradient about 1˚. The center of the lacustrine basin is located in the southeast, roughly in Qijia-Gulong Depression (Figure 3).

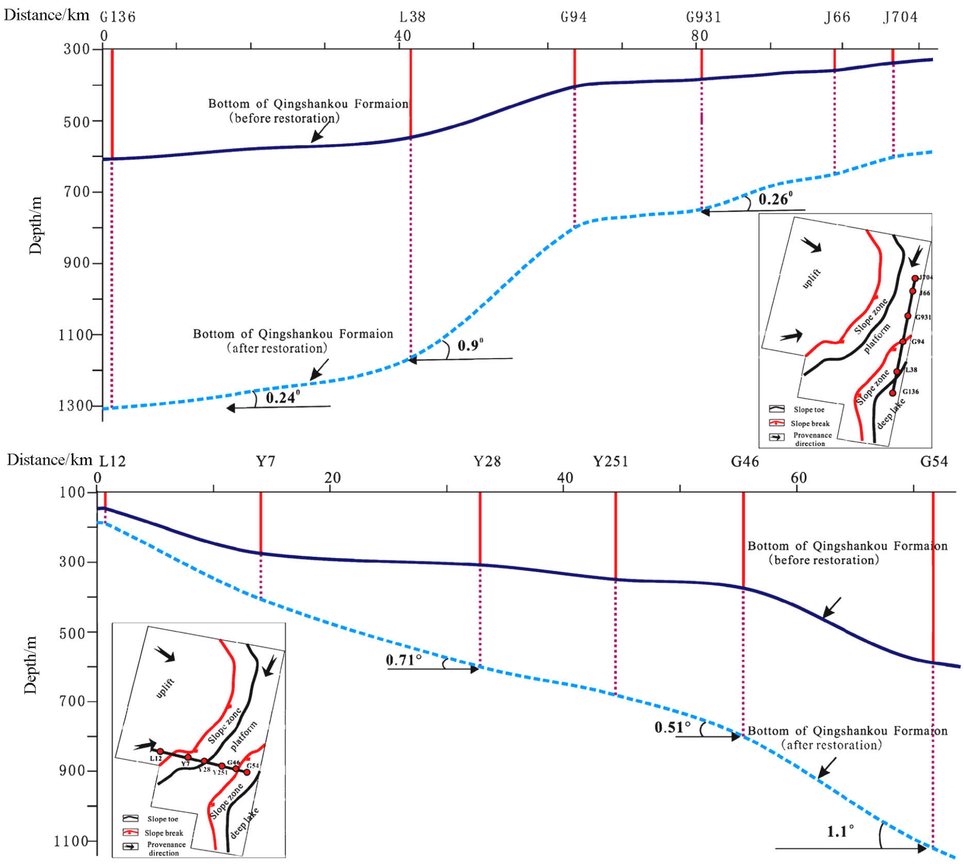


Figure 3. The palaeomorphology of early Qingshankou formation.

Late in the Qingshankou Formation, the West Slope Area is still controlled by two slope belt, including the upper slope belt and the lower slope belt. The upper slope belt still has a southwest-northeast trend with the width about 12 - 16 km. The slope gradient is slightly gentle (about 0.7˚). And the upper slope belt migrates to southeast compared with the earlier study in the Qingshankou Formation. The lower slope belt has a southwest-northeast trend with the width about 13 - 16 km, and slope gradient about 0.9˚. The center of the lacustrine basin is still located in Qijia-Gulong Depression (**Figure 4**).

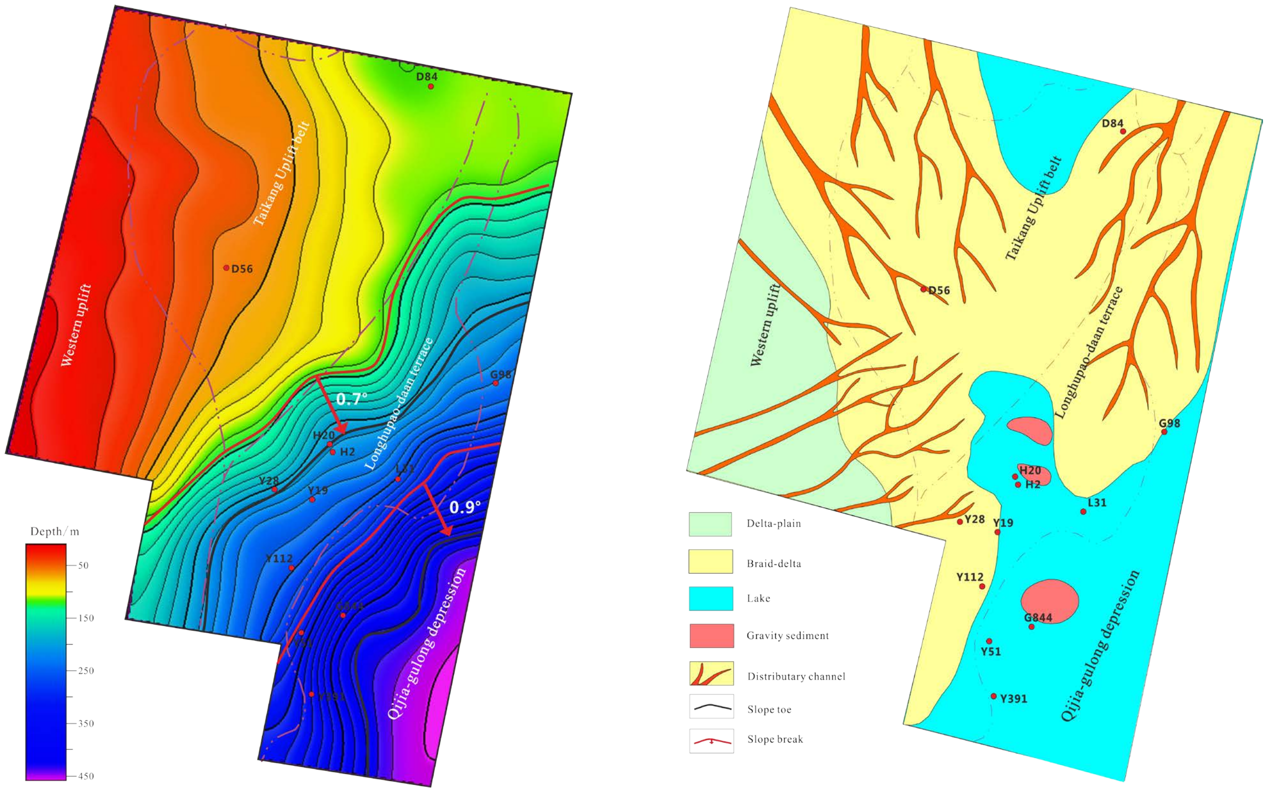
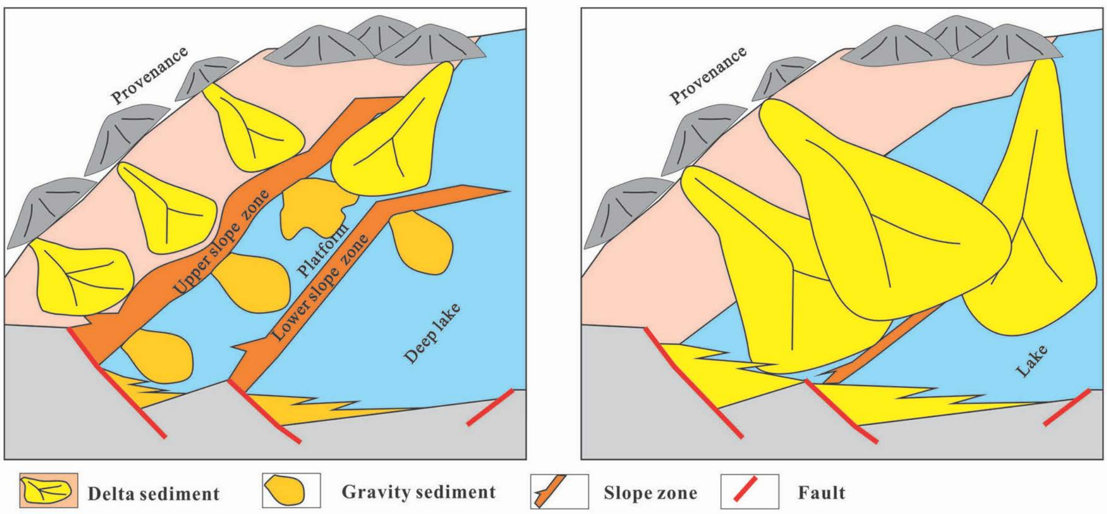


Figure 4. The palaeomorphology and sedimentary system of late Qingshankou formation.

Influenced by the early stage of the sediment filling, the slope gradient of Yaojia Formation gets significantly gentle. The West Slope is mainly controlled by single slope belt. The upper slope belt vanishes as the slope gradient is about 0.1˚, which has little effects on sediment distribution. The lower slope belt has a southwest-northeast trend, width is about 13 - 16 km, and slope gradient drops to 0.4˚.

5.2. Development Pattern of Sand Bodies under Influence of Provenance-Sink

The early Qingshankou Formation mainly develops delta plain, delta front sediments, which comes from Qiqihar Provenance in the northwest and Yingtai Provenance in the west. Large area of gravity sediment is deposited under the steep upper slope belt, such as Region H2 - H20, Region Y28 - Y19. Under the lower slope belt, the sediments from the provenance in the west are relatively thin, and the supply energy is low, and difficult to push the sediments forward. Therefore, under the lower slope, large segment of mud deposition is predominant, and the gravity flow deposition is less developed (Figure 5(a)). At the same time, the sediments from the north provenance is developed on the platform. As the delta front sediments are parallel to the slope belt, they are overlaid on the upper slope belt. The upper slope belt forms a channel for transporting the provenance system in the north, and the channel terminates near the lower slope belt. Thus the gravity flow deposits are formed by sediment sliding down the lower slope (Figure 5(a)).



(a) Early Qingshankou Formation (b) Yaojia Formation

Figure 5. The sand development model under the control of slope and provenance in west slope area.

At the early stage of the Qingshankou Formation, the study area is a lacustrine sedimentary environment. Only sand bodies are developed at the edge of the lake, and sand bodies are less developed under the slope belt (Figure 5(a)). With the filling of sediment at the later stage, the slope zone gradually becomes gentle and the controlling effect on sediment is weakened. During the period of Yaojia Formation, the sediment provenance kinetic energy is enhanced. The provenance propulsion in all directions is obvious and the delta front sand body is widely distributed in the study area (Figure 5(b)).

To sum up, the terrain of the Qingshankou Formation in the West Slope is controlled by two slope zones. The combination of upper and lower slope zones controls the distribution of reservoir genetic types. The upper slope belt parallel to the provenance direction forms the channel for supplying provenance and controls distribution characteristics of the reservoir. At the early stage of Yaojia Formation, the gradient of the slope belt gradually becomes gentle, and the delta sand bodies are widely distributed.

6. The Control Factor of Reservoir Distribution

The main factors controlling the genetic types and distribution of reservoirs in the basin include tectonism, climate, and sediment supply and lake level [22]. Tectonism plays an important role in controlling sedimentary system in non-marine basins [23]. Paleotectonic movement influences the size of accommodating space through changing the paleogeomorphology, and controls the genetic type and distribution of sedimentary system. Qingshankou Formation in the Western Slope is at the stage of depression, and the basin continues to subside due to regional extension. There are two slope belts developed in Qingshankou Formation. The upper slope belt is relatively steep, thus, the accommodating space is limited below the slope. Gravity sediments and the delta front deposits are mixed under the slope zone. Small amount of tuff-like turbidite is developed under the slope zone of the lower slope belt (**Figure 6**).

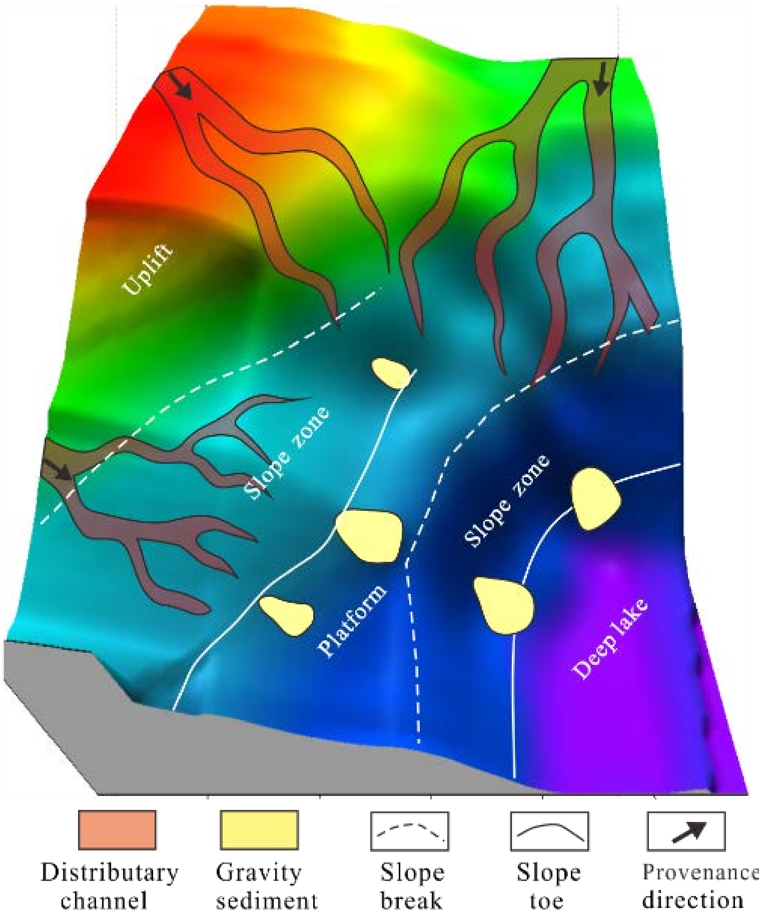


Figure 6. The reservoir development mode of Qingshankou Formation in West Slope of SL Basin.

The variation of lake level plays an important role in controlling the filling model of lacustrine basin. However, in the over-filling basin, the effect of climatic conditions is very small [24]. The subsidence rate of the Western Slope is less than 10 m/Ma [25]. Rapid transgression in the Qingshankou Formation induces the deposition of deep lake, which is a state of hungry filling. The sand bodies is developed only at the edge of lacustrine basin, and less distributed under slope zone. The combination of sediment provenance and slope belts also plays an important role in controlling sedimentary types and distribution. During the stage of Qingshankou Formation, the provenance direction is consistent with the slope belt, and the slope belt forms a transport channel for the provenance system. If the provenance direction is perpendicular to the slope belt, the delta terminates near the slope belt and isolated gravity flow deposition is developed under the slope belt (**Figure 6**). Therefore, the paleogeomorphology, lake level and sediment provenance jointly affected the Western Slope Area, by which variety of sedimentary systems are developed.

7. Conclusions

1) The Western Slope is controlled by two slope belts at the stage of Qingshankou Formation. The terrain of Yaojia Formation is gentle and the Western Slope is mainly controlled by a single slope belt.

2) The two slope belts comprehensively affect the reservoir genetic type in the Western Slope, and the direction of sediment provenance and the slope belt jointly control the reservoir distribution, and the sediment supply rate affects the scale and distribution of sand body.

3) Paleogeomorphology, lake level and sediment provenance are the main controlling factors of sediment in the Western Slope.

Conflicts of Interest

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

References

[1] Wang, S.H., Wu, H.Y., Xin, R.C., *et al.* (1996) Study on Sedimentary Microfacies of No. 3 Sand Group of Gaotaizi Reservoir in West Slope in Northern SL Basin. *Petroleum Geology & Oilfield Development in Daqing*, **25**, 10-12.

[2] Hu, X.L., Fan, T.L., Zhang, X.L., *et al.* (2011) Sedimentary Micro-Facies Research and Provenance Analysis of the SII III Sand Groups of Yaojia Formation in the West Slope of Northern SL Basin. *Journal of Jilin University* (*Earth Science Edition*), **41**, 647-656.

[3] Zhang, J.L., Lin, C.S., Zheng, R.H., *et al.* (2002) Controlling Action of Fractures, Palaeogeomorphology and Sediment Provenances of Rift Lake-Basin on Sedimentary System-Taking Es3 *Gubei subsag* as Example. *Petroleum Geology and Recovery Efficiency*, **4**, 24-27.

[4] Shi, Z.S., Wang, T.Q., Wang, J.G., *et al.* (2012) Application of Seismic Sedimentology to Sand Body Identification under Different Geological Settings: A Case Study from the Western Slope and Placanticline of SL Basin. *Lithologic Reservoirs*, **23**, 5-10.

[5] Zhou, Z., Feng, D., Wang, H.L., *et al.* (2012) Sequence Stratigraphy Framework of Qing 1 and Qing 2 Members in the Western Slope of Southern SL Basin and Its Control Effect on Reservoir Sand Bodies. *Lithologic Reservoirs*, **24**, 42-47.

[6] Xie, W.R., Niu, J.Y., Wang, H.L., *et al.* (2008) Study on Lithologic Reservoirs in

Yuanyanggou Area of Liaohe Depression. *Lithologic Reservoirs*, **20**, 75-79.

[7] Xin, R.C. and Wang, Y.M. (2004) Origin and Evolution of West Slope Breaks of Qingshankou-Yaojia Formation in Northern SL Basin. *Earth Science—Journal of China University of Geosciences*, **29**, 621-624.

[8] Xin, R.C., Cai, X.Y. and Wang, Y.M. (2004) Analyzing Action of Slope Belt in Western Slope Area, South of SL Basin. *Acta Sedimentologica Sinica*, **22**, 387-392.

[9] Guo, W., Liu, Z.J., Cui, B.C., *et al.* (1997) Characteristics of Valley-Slope Belt in the Western Slope of SL Basin and Its Control over Reservoir Distribution. *Journal of Changchun Geological Institute*, **27**, 327-332.

[10] Gao, R.Q. and Xiao, D.M. (1995) New Development of Oil and Gas Exploration in SL Basin and Its Periphery. Petroleum Industry Press, Beijing, 121-185.

[11] Wang, H.J. and Cao, W.F. (1981) Pattern of Cretaceous Sedimentary Facies in SL Basin. *Oil & Gas Geology*, **3**, 227-242.

[12] Shanmugam, G. (2000) Deep-Water Processes and Facies Model: A Critical Perspective. *Marine and Petroleum Geology*, **17**, 285-342. https://doi.org/10.1016/S0264-8172(99)00011-2

[13] Shanmugam, G. (2002) Ten Turbidite Myths. *Earth Science Reviews*, **58**, 311-341. https://doi.org/10.1016/S0012-8252(02)00065-X

[14] Xin, R.C. and Wang, Y.M. (2004) Characteristics of Valley-Slope Belt in the Western Slope of SL Basin and Its Control over Reservoir Distribution. *Earth Science—Journal of China University of Geosciences*, **29**, 621-624.

[15] Cui, L.T., Feng, D., Qin, Y.Q., *et al.* (2013) Palaeogeomorphology Reconstruction and Sand Body Distribution of Chang 7 Reservoir in Zhenbei Area, Ordos Basin. *Lithologic Reservoirs*, **25**, 65-69.

[16] Jiu, K., Ding, W.L., Li, C.Y., *et al.* (2012) Advances of Paleostructure Restoration Methods for Petroliferous Basin. *Lithologic Reservoirs*, **24**, 13-19.

[17] Sciunnach, D. and Garzanti, E. (2012) Subsidence History of the Tethys Himalaya. *Earth-Science Reviews*, **111**, 179-198. https://doi.org/10.1016/j.earscirev.2011.11.007

[18] Cui, L.T., Hao, S., Wang, C.P., *et al.* (2015) Palaeogeomorphology Reconstruction and Sand Body Distribution of the Chang 7-6 Intervals of Triassic Yanchang Formation in Northern Zhenyuan Area, Ordos Basin. *Journal of Palaeogeography*, **17**, 805-812.

[19] Feng, D., Deng, H., Zhou, Z., *et al.* (2015) Paleotopographic Controls on Facies Development in Various Types of Braid-Delta Depositional Systems in Lacustrine Basins in China. *Geoscience Frontiers*, **6**, 579-591. https://doi.org/10.1016/j.gsf.2014.03.007

[20] Jiang, Z.L. and Deng, H.W. (2009) Methods and Application of Paleo-Geomorphologies Rebuilding: An Example of the Second Member of Shahejie Formation, Zhuangxi Area, Jiyang Depression. *Geoscience*, **23**, 865-870.

[21] Zhang, S.Q. and Ren, Y.G. (2003) The Study of Base Level Changes of the SL Basin in Mesozoic. *Journal of Earth Sciences and Environment*, **25**, 1-5.

[22] Posamentier, H.W. and Allen, G.P. (1993) Variability of the Sequence Stratigraphic Model: Effects of Local Basin Factors. *Sedimentary Geology*, **86**, 91-109. https://doi.org/10.1016/0037-0738(93)90135-R

[23] Lin, C.S., Yang, H.J. and Liu, J.Y. (2009) Paleostructural Geomorphology of the Paleozoic Central Uplift Belt and Its Constraint on the Development of Depositional Facies in the Tarim Basin, Science in China Series D. *Earth Sciences*, **52**, 823-834.

https://doi.org/10.1007/s11430-009-0061-8

[24] Carroll, A.R. and Bohacs, K.M. (1999) Stratigraphic Classification of Ancient Lakes: Balancing Tectonic and Climatic Controls. *Geology*, **27**, 99-102. https://doi.org/10.1130/0091-7613(1999)027<0099:SCOALB>2.3.CO;2

[25] Guo, S.B., Qu, Y.B. and Wang, S.X. (1998) Model of Terrestrial Basin Sequence and Systems Tract: Taking the Western Slope SL Basin as an Example Geological Science and Technology. *Geological Science and Technology Information*, **17**, 37-42.