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Identification of High-Quality Transverse Transport Layer Based on Adobe Photoshop Quantification (PSQ) of Reservoir Bitumen: A Case Study of the Lower Cambrian in Bachu-Keping Area, Tarim Basin, China

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Abstract: The Lower Paleozoic carbonate reservoir in the Tarim Basin is a hotspot area for deep oil and gas exploration in China. Although the Lower Cambrian of the Bachu Uplift has not encountered industrial oil flow, rich bitumen has been found there. As the most direct trace of petroleum migration, the effective identification of bitumen is the key to studying the hydrocarbon transportation path. In this study, the Adobe Photoshop quantification (PSQ) method is used to identify the bitumen content in the Xiaoerblak Formation in Well Shutan 1, and, combined with the bitumen characteristics of the Shihuiyao section, a high-quality petroleum transverse transport layer is determined. The results indicate the following: (1) In Well Shutan 1, bitumen is mainly concentrated in the middle and upper parts of the Xiaoerblak Formation with high porosity and high permeability. (2) The shale of the Yuertus Formation in the Shihuiyao section has low hydrocarbon generation potential. However, the overlying Xiaoerblak Formation has developed multistage bituminous veins and bitumen-encapsulated gravels, which is the result of multiple instances of horizontal hydrocarbon migration. (3) After combining the bitumen characteristics of Well Shutan 1 and the Shihuiyao section, it is confirmed that there are high-quality lateral transport conductors in the middle and upper parts of the Xiaoerblak Formation, and the Subsalt Cambrian dolomite reservoir has great exploration potential.

Keywords: transverse transport layer; reservoir bitumen; marine carbonate rocks; Lower Cambrian; Adobe Photoshop quantification (PSQ)

1. Introduction

In recent years, the global oil and gas research trend has gradually shifted to "threedeep areas". The oil and gas display in the Tabei-Tazhong Uplift of the Tarim Basin and the strategic discovery of the Sinian-Cambrian Anyue giant gas field in the Sichuan Basin confirm that the Paleozoic carbonate reservoirs in China have extensive oil and gas properties [1–4]. The Tarim Basin has developed large-scale Cambrian dolomite strata, with a distribution area of more than 20×10^4 km² and a thickness of nearly 1400 m [4,5]. There are several high-quality dolomite reservoirs in the Xiaolbulak Formation [6–8], and underlying them are the high-quality source rocks of the Yuertus Formation at the basin level [9,10] and overlying them are the gray argillaceous dolomite cap rocks of the Middle Cambrian Wusonger Formation. The Xiaoerblak Formation has superior source, reservoir and capacity conditions [11]. However, the study area has experienced multistage tectonic events, most oil and gas reservoirs have been damaged and reconstructed, and the petroleum transport path has become complex and diverse [12].

A large amount of bitumen has been discovered in the Lower Cambrian in the Bachu-Keping area, confirming that large-scale hydrocarbon migration occurred in the Xiaoerblak



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Formation. Constrained by the longer drilling times and the few core samples of Well Shutan 1, the bitumen content cannot be obtained by bitumen extraction. Furthermore, the method of calculating carbonate reservoir bitumen content by logging data at home and abroad is only carried out using NMR logging [13]. However, there are no NMR logging data, and it is too difficult to calculate the carbonate reservoir's bitumen content using conventional logging. Therefore, image processing software has been used to identify the bitumen content in the cast thin section. Digital imaging technology has been applied numerous times to study the rock's thin section. Nishimoto used Photoshop to conduct a modal analysis of granite [14]; J. V. White proposed a method to obtain porosity values from digitized slice images using NIH Image software [15]; and Zhang Xuefeng quantified rock structure data and porosity using Photoshop [16]. As image processing software with strong practicality and tools, and with its color processing and analysis functions, Photoshop can be used to analyze geological data. Therefore, the Adobe Photoshop quantification (PSQ) method can be used to identify the bitumen content of the cast thin section. Compared with the visual estimation method, the point method [17,18] and traditional thin-section image analysis [19], the PSQ method undoubtedly has the advantage of higher accuracy. In this study, the PSQ method was used to analyze the relationship between the reservoir bitumen content and the petrophysical characteristics in Well Shutan 1, and, combined with the different bitumen charging content and stages of the Lower Cambrian in the vertical direction of the Shihuiyao section, high-quality lateral transport layers in the Xiaoerblak Formation were identified.

2. Geological Setting

The Tarim Basin is located in the northwest of China and in the south of the Xinjiang Uygur Autonomous Region, and its Lower Paleozoic marine carbonate reservoirs contain a large number of oil and gas resources [20,21]. The Bachu Uplift is a thrust anticlinal structural belt located in the west of the central uplift belt [22]. Well Shutan 1 is located at the structural high point of the northwestern edge of the Bachu Uplift, and it does not encounter the Lower Cambrian Yuertus Formation [23]. Although there is no obvious oil and gas display, a large amount of bitumen has been found in the core sections. The Shihuiyao section, located in the northwest margin of the basin, developed a central sliding crushing belt, and the Lower Cambrian is continuous and outcropped [24]. From the late Middle Caledonian period to the Haixi Period, the South Tianshan Ocean subducted to the Tarim Plate. The Shihuiyao section was uplifted under the action of north–south stress, and it developed a large number of NNE- and NE-directional faults (Figure 1).



Figure 1. Geological setting of the study area: (a) location map of Bachu-Keping area in Tarim Basin;(b) lithological profile of Well Shutan 1; (c) tectonic cross-section of Shihuiyao section.

3. Experimental Samples and Method

3.1. Samples

The core sections in the Upper Xiaoerblak Formation in Well Shutan 1, 1883.21–1889.51 m and 1915.00–1919.43 m, are mainly micritic and fine crystal dolomite, with dissolutionenlarged pores and inter-granular pores, mineral particles up to 1.1 mm in size and dolomite crystals being straight-faced idiomorphic. There are dolomite-filled holes, micro-cracks cut through sutures and dolomite fillings, confirming that it has experienced multistage diagenesis. The abundant bitumen attached to the pore walls and completely filled in pores, cavities and fractures confirm that the layers are high-quality petroleum transport conductors (Figure 2a–f). The lithology of the core sections at 1988.67–1996 m and 2057.39–2064.69 m in the Lower Xiaoerblak Formation is mainly powdery and fine-grained dense dolomite with poor petrophysical characteristics, and some pyrite and weak crude oil dissemination can be seen here (Figure 2g–i). In contrast, the middle and upper parts of the Xiaoerblak Formation, with high porosity, high permeability and richer bitumen, are high-quality dolomite reservoirs.



Figure 2. Photos of cast thin sections of cores in Well Shutan 1: (**a**) 1883.5 m, dolomicrite, hydrocarbon charged and adhered to the pores in wall; (**b**) 1884.85 m, algal straticulate dolostone, sutures filled by hydrocarbon and cut by microfractures; (**c**) 1886.2 m, crystal powder dolomite and mesocrystalline dolomite, hydrocarbon-filled intergranular dissolution pores of mesocrystalline dolomite; (**d**) 1887.6 m, fine crystal dolomite on the left, disorderly distribution of algal debris in the center, fine crystal powder dolomite on the right, intergranular pores completely filled with hydrocarbon on the left side, only a few hydrocarbons on the right; (**e**) 1916.1 m and (**f**) 1918.35 m, fine crystalline dolomite, abundant intergranular dissolution pores, contains bitumen; (**g**) 1990.1 m, densified silty dolomite, crude oil disseminated in intragranular and intergranular pores; (**h**) 1993.9 m and (**i**) 2058.4 m, dense dolomite, pyrite densely developed.

3.2. PSQ Method of Bitumen Identification

The Xiaoerblak Formation in Well Shutan 1 is dominated by pore and cave dolomite reservoirs. In the cast thin sections, bitumen is black, pores are blue, rock is gray, and the

colors between them are very easy to distinguish. In pictures, the "Color Range" tool can precisely select a particular color, and it records the pixel values of all the areas of the color. By calculating the ratio of the pixels between the bitumen, porosity and the entire image, the bitumen content and porosity can be obtained. The process of using the PSQ method to identify bitumen content in the cast thin section is as follows:

- (1) Select "Color Range" in the "Selection bar", pick the bitumen color in the thin section using the "Sampling pen" tool and then adjust the selection area by changing the "color tolerance" (in this study, the best "color tolerance" of bitumen was around 100). If the color of the cast thin section is complex, it is necessary to adjust the color level, brightness and contrast so that bitumen and rock can be easily distinguished.
- (2) Secondary adjustments require geological knowledge to eliminate areas where a color is similar to that of bitumen but is not bitumen. For example, pyrite appears black under orthogonal light microscopy, similar in color to bitumen, but it appears yellowgreen under cathodoluminescence (Figure 3). Then, record the pixel values of the selected bitumen area.



Figure 3. Microscopic identification characteristics of pyrite in Well Shutan 1: (**a**,**c**) orthogonal optical images; (**b**,**d**) cathodoluminescence images.

- (3) Use "Color Range" to pick the pore color, and adjust the selection area by changing the "color tolerance" (in this study, the best "color tolerance" for the pores was 40–50). Then, record the pixel values of the selected pore area.
- (4) Select the whole thin section with the "Rectangular Marquee" tool, and record the pixel values of the cast thin section.
- (5) The percentage of bitumen content in the thin section and the pores can be obtained by calculating the bitumen pixels divided by the pixels of the thin section and pores.
- (6) Steps 1–5 describe how to calculate bitumen content in a picture; however, there are usually 10–20 cast thin sections at any one depth data point. Repeat the above steps to calculate the bitumen content of all the cast thin sections at a certain depth, and then calculate its average value to obtain the bitumen content at this depth.

We demonstrate the PSQ method by taking the depth of 1885.4 m in Well Shutan 1 as an example. Firstly, we analyze a single image: the pixel value of the whole thin section is 1,228,800, the pixel value of the blue pore area is 99,646, and the pixel value of the black bitumen area is 31,389 (Figure 4).



Figure 4. Pixel values of the cast thin section at a depth of 1885.4 m in Well Shutan 1: (**a**) thin section; (**b**) bitumen; (**c**) pores.

According to the process above, we obtain the following results:

The percentage of the bitumen content in the pores is 31,389/(31,389 + 99,646) = 29.54%. The percentage of the bitumen content in the thin section is 31,389/1,228,800 = 2.55%. The surface porosity of the thin section is (99,646 + 31,389)/1,228,800 = 10.66%.

Secondly, we calculate the average value of the bitumen content in the pores of all 9 thin sections at the depth of 1885.4 m in Well Shutan 1. The result shows that, at a depth of 1885.4 m, the percentage of bitumen in the pores in Well Shutan 1 is 35.27% (Figure 5).



Figure 5. Bitumen content in pores identified using the PSQ method at a depth of 1885.4 m in Well Shutan 1.

Finally, after we process 523 cast thin sections images of the Xiaoerblak Formation in Well Shutan 1 and exclude some extreme values, we obtain 25 depth data points. The porosity and the bitumen content in the pores and in the thin sections at each depth data point can be calculated using the PSQ method (Table 1).

Depth /m	Bitumen Content in Thin Section /%	Bitumen Content in Pores /%	PSQ Porosity /%	Logging Porosity /%	Core Porosity /%	Core Permeability /10 \times 10 $^{-3}~\mu\text{m}^2$	Core Section
1883.5	2.28	76.95	2.97	3.92	3.23	0.086	
1884.85	1.34	59.58	1.66	4.27	/	/	
1885.4	3.12	35.27	6.01	4.32	/	/	
1885.8	4.24	33.65	5.73	5.19	8.12	0.064	1st
1886.2	4.97	55.05	9.24	8.11	8.96	0.06	
1886.75	4.23	54.86	5.34	5.52	3.99	0.054	
1887.6	1.66	33.33	3.08	3.80	/	/	
1915.1	3.44	15.31	15.37	15.10	13.32	33.492	
1915.45	3.30	15.01	16.43	14.61	15.87	34.2	
1916.1	1.86	11.06	14.73	13.17	11.43	40	0 1
1917.1	0.32	3.87	8.80	10.30	9.81	18	2nd
1917.6	1.28	10.23	17.64	13.67	17.33	13.8	
1918.35	1.39	8.64	10.35	8.48	/	/	
1988.67	0.05	/	0.35	0.30	0.60	0.002	
1989.27	0.09	/	0.40	0.55	0.58	0.691	
1990.6	0.05	/	0.71	0.92	0.54	0.002	3rd
1990.8	0.09	/	0.12	0.80	0.74	0.002	
1991	0.12	/	0.56	0.84	0.74	0.001	
1993.1	0.00	/	0.89	0.69	0.53	0.001	
1993.6	0.00	/	0.43	0.58	0.44	0.001	
1994.3	0.00	/	0.22	2.28	0.93	0.001	
1994.8	0.00	/	2.89	2.54	2.28	0.686	
2058.4	0.00	/	0.33	1.05	0.19	0.001	
2058.7	0.08	/	0.56	1.76	0.78	0.176	4th
2063	0.00	/	0.31	1.34	0.19	0.001	

Table 1. Bitumen content, porosity and permeability of core sections in Well Shutan 1.

In order to verify the accuracy of the PSQ method, we compare the logging porosity and core porosity with the surface porosity calculated using the PSQ of Well Shutan 1 (Table 1). The previous methods used to calculate the porosity of carbonate rocks generally take the porosity φ DN calculated by density/neutron logging as its total porosity φ T [25,26]. This shows that the measured porosity and the porosity of the PSQ have a good linear relationship; the slope is close to 1, and the intercept is extremely small (Figure 6). Therefore, the rationality of using the PSQ method to calculate porosity is relatively high, which further confirms the rationality of the PSQ method for the processing of images of thin sections.



Figure 6. Linear graph of porosity of PSQ and measured porosity in Well Shutan 1.

4. Results

4.1. Reservoir Bitumen Characteristics of Lower Cambrian in Well Shutan 1

The concept of a hydrocarbon transport conductor was first proposed by Galeazzi [27] in his study of the Malvinas Basin. The conducting conductor refers to the three-dimensional channel space for fluid and petroleum migration formed by interconnected and highly permeable pores, holes and fractures [28–33]. Although industrialized oil and gas flows have been discovered in the deep Cambrian in Wells Zhongshen 1, Zhongshen 5 and Luntan 1, no obvious oil and gas display has been obtained from other wells. The transport system is not only a space for oil and gas migration but also a potential place for oil and gas accumulation and a channel for oil and gas overflow and dispersion [34,35]. Reservoir bitumen is mainly formed by the continuous reduction of light components in the processes of hydrocarbon discharge, transportation and accumulation. Therefore, the abundant reservoir bitumen of the Lower Cambrian in Well Shutan 1 (Figure 2) represents the identification of oil and gas migration and dissipation.

The effective identification of bitumen content has become the key to studying the hydrocarbon transportation path of the Lower Cambrian carbonate reservoir in the Tarim Basin. In this study, it was found that the bitumen content in the upper two core sections of the Xiaoerblak Formation, with higher measured porosity and permeability in Well Shutan 1, was significantly richer than that at the bottom (Table 1 and Figure 7), proving that the middle and upper parts of the Xiaoerblak Formation were important petroleum migration channels. Comprehensive analysis shows that the high-porosity and high-permeability dolomite layers in the middle and upper parts of the Xiaoerblak Formation during their geological history, so they are high-quality lateral petroleum transport conductors.



Well Shutan 1

Figure 7. Porosity, permeability and bitumen content of Xiaoerblak Formation in Well Shutan 1.

4.2. Reservoir Bitumen Characteristic of Lower Cambrian in Shihuiyao Section

The Lower Cambrian in the Keping area is exposed to the surface, and the deposition is relatively continuous, so it can be used as a high-quality lateral reference object for Well Shutan 1. With the expansion of oil and gas exploration, scholars generally agree that the main source rock of the Lower Paleozoic in the Tarim Basin is the Yuertus Formation [9,10]. The lithology of the Yuertus Formation in the Shihuiyao section is mainly phospho-bearing siliceous rock and dolomite, and the potential for hydrocarbon generation is poor. Furthermore, many longitudinal fractures with single-stage calcite veins have developed in the Yuertus Formation, as well as single-stage bitumen attached to the inner wall of the calcite. The above phenomenon proves that there was a single period of hydrocarbon charging in the Yuertus Formation (Figure 8).



Figure 8. Single-stage bitumen vein of the Yuertus Formation in the Shihuiyao section: (**a**) top of the Yuertus Formation; (**b**) bottom of the Yuertus Formation.

Through a field investigation and sampling analysis of the Xiaoerblak Formation in the Shihuiyao section, we found that there is abundant bitumen in its cracks and pores. First, from the perspective of macroscopic cracks, there are three types of bitumen-filling phenomena. The first type developed single-stage bitumen veins in cracks such as the Yuertus Formation, and they are mainly located at the bottom of the Xiaoerblak Formation (Figure 9a). The second type is mainly located in the middle and upper parts of the Xiaoerblak Formation, where multistage bitumen and calcite are alternately charged in the fractures (Figure 9b). The third type mainly developed in the Upper Xiaoerblak Formation, where a large number of gravels of various sizes have filled the cracks and are covered by bitumen (Figure 9c). It is worth noting that the bitumen content in the fractures of the Upper Xiaoerblak Formation is significantly higher than that at the bottom. Second, from the perspective of microscopic pores, three sets of bituminous dolomite layers can be identified in the Shihuiyao section. In the middle part of the Lower Xiaoerblak Formation, bitumen distribution in the dissolution expansion pores is rare, and a significant amount of bitumen only exists in individual layers. Dissolution-enlarged pores developed in the middle and upper parts of the Xiaoerblak Formation, where bitumen is abundant. The crystal powder dolomite and the granular dolomite in the Upper Xiaoerblak Formation mainly developed dissolution-enlarged pores and mold pores of grain where the bitumen content is the highest (Figure 10).



Figure 9. Different bitumen phenomena of Xiaoerblak Formation in Shihuiyao section: (**a**) single-stage bitumen vein at bottom; (**b**) multistage bitumen veins in the middle and upper parts; (**c**) bitumencoated gravel in the upper part.



Figure 10. Comprehensive bitumen display in the Lower Cambrian in Shihuiyao section.

There is large-scale reservoir bitumen in the Lower Cambrian of the Shihuiyao section. The vertical bitumen content in the pores of the Xiaoerblak Formation in the Shihuiyao section (Figure 10) is similar to that in Well Shutan 1 (Figure 7); that is, the Upper Xiaoerblak Formation, with better petrophysical characteristics, has more abundant bitumen, which reveals that petroleum migrated laterally mainly along the upper part on the inside of the Xiaoerblak Formation. In addition, single-stage bitumen veins can be seen in the fractures of the Yuertus Formation and the Lower Xiaoerblak Formation, and multistage bitumen veins can be seen in the middle and upper parts of the Xiaoerblak Formation. Comprehensive analysis reveals that, after hydrocarbon generation in the Yuertus Formation of other areas, a small amount of oil and gas migrated horizontally along the Yuertus Formation and the bottom of the Xiaorblak Formation to the Shihuiyao section and filled the fractures, thus forming single-stage bitumen veins. In addition, most of oil and gas horizontally migrated to the Shihuiyao section along the high-quality dolomite lateral transport layers in the middle and upper parts of the Xiaoerblak Formation and charged into the fractures, resulting in the multistage bituminous veins and bitumen-encapsulated gravels.

5. Discussion

The Lower Paleozoic carbonate oil and gas in China account for 69% of the total marine oil and gas, while the proved rate is only 6.3%. Therefore, deep marine carbonate rock will be an important oil and gas replacement area in China in the future [36,37]. We conducted oil and source rock correlation between the Middle and Lower Cambrian bitumen from the Shihuiyao section and Cambrian source rocks from three different sections (the Shihuiyao section, Sugaitebulak section and Linkuanggou section). The results show that the reservoir bitumen has a good correlation with the source rock of the Yuertusi Formation. The Yuertus Formation of the Lower Cambrian is the most important source rock of the Lower Paleozoic, and the discovered Ordovician reservoirs are far away from the Yuertus Formation source rocks in the Manjiaer depression. The future exploration direction of the largest petroliferous, superimposed basin in China will be determined by whether large-scale lateral petroleum migration occurred along the Ordovician or Lower Cambrian. Industrial oil and gas reservoirs were found in the Lower Cambrian Xiaoerblak Formation and the Middle Cambrian Shayilike Formation, respectively, in Wells Zhongshen 1 and Luntan 1, indicating that the transverse transport layers of the Middle and Lower Cambrian control the deep oil and gas migration in the Tarim Basin. Furthermore, most abundant reservoir bitumen developed in the middle and upper parts of the Xiaoerblak Formation, with high porosity and high permeability, which proves its effectiveness as a high-quality lateral transport layer.

6. Conclusions

Based on the PSQ method used to identify the bitumen content of the cast thin sections in Well Shutan 1 and a field survey conducted on the Shihuiyao section, we draw the following conclusions:

- (1) There is a lot of reservoir bitumen in Lower Cambrian of Well Shutan 1. The high-porosity and high-permeability layers in the middle and upper parts of the Xiaoerblak Formation have significantly higher bitumen content than the lower part, and, therefore, the middle and upper parts of Xiaoerblak Formation is a high-quality oil and gas transport interval.
- (2) Whether from macroscopic fractures or microscopic pores, the bitumen content in the middle and upper parts of the Xiaoerblak Formation in the Shihuiyao section is obviously higher than that at the bottom. Due to fact that the Yuertus Formation of the Shihuiyao section has no hydrocarbon generation conditions, hydrocarbon can only be generated from other areas and migrates horizontally to the Shihuiyao section. A small amount of oil and gas migrated laterally along the Yuertus Formation and the bottom of the Xiaoerblak Formation and formed a single-stage bitumen vein. Most petroleum migrated laterally along the high-quality dolomite transport layers in the

middle and upper parts of the Xiaoerblak Formation to the Shihuiyao section, where the fractures were charged multiple times and formed multistage bituminous veins and bitumen-encapsulated gravels.

(3) A large amount of oil and gas migration occurred in the middle and upper parts of the Lower Cambrian Xiaoerblak Formation with high porosity and high permeability in the Bachu-Keping area, and they are high-quality petroleum transverse transport layers. In addition, considering the excellent source, reservoir and cap conditions of the Xiaoerblak Formation, its oil and gas exploration potential is huge.

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