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Evaluation of the Geological Characteristics and Exploration Potential of Tight Oil in the Neogene Upper Ganchaigou Formation in the Zhahaquan Area, Qaidam Basin

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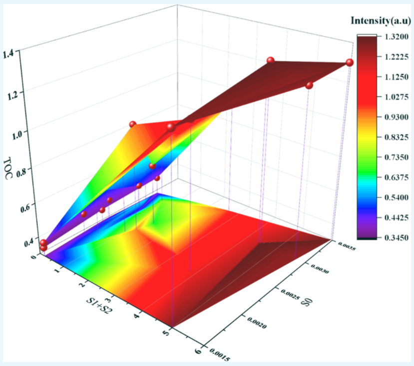
ABSTRACT: The study of the geochemical characteristics of source rocks is an important part of tight oil evaluation. The Zhahaquan area of the Qaidam Basin is a new area for tight oil exploration in China. During the sedimentary period of the Neogene Upper Ganchaigou Formation (N1) in the Zhahaquan area, a set of source rocks of semideep lake and deep lacustrine facies as well as a set of thin, interbedded fine sandstone and argillaceous limestone was deposited, providing favorable conditions for the formation of tight oil. However, the study on the geochemical characteristics of source rocks in this area is relatively weak. The geochemical characteristics of the source rocks in the Zhahaquan area were determined via the experimental analysis of parameters such as vitrinite reflectance (Ro), chloroform bitumen "A", total organic carbon (TOC), group components, kerogen types, rock pyrolysis, and aromatic compounds of crude oil. The following results were obtained: the Zhahaquan area had II_1-type hydrocarbon source rock organic matter, and the TOC was 0.32%−1.32%. The type index (TI) was 48.70−72.23, the chloroform bitumen "A" content was 0.0034%−0.1133%, Ro was 0.810%−1.265%, and the cracking hydrocarbon peak temperature (T_{max}) was distributed in the temperature range of 362−444 °C. The hydrocarbon generation conversion rate was 0.89%−10.0%. The reservoir mainly had intergranular pores, dissolution pores, and microfractures. The average porosity was 8.0%, and the average permeability was $0.861 \times 10^{-3}\ \mu m^2$. The average oil saturation was 30.0%, and the average water saturation was 21.6%. From a comprehensive analysis of the results, the following inferences were derived. The parent material of the source rocks in the Zhahaquan area mainly originated from algae and other phytoplankton in the lake basin, which was a good source rock for oil exploration. The source rocks of this area have entered the threshold of hydrocarbon generation and are in the peak oil-generation stage. They have potential as industrial oil and gas resources. The oil test results of YD103 and seven other wells showed that the daily oil index per meter ranges from 0.38 to 6.5 m^3/d·m, indicating that the source rocks have the ability to form industrial oil. Analysis of the geochemical characteristics of source rocks and study of reservoir geological characteristics will provide theoretical support and reference for tight oil exploration and development in Zhahaquan.



1. INTRODUCTION

Tight oil refers to oil resources that are concentrated in tight reservoirs surrounded by high-quality source rocks or adjacent to high-quality source rocks without having been transported over long distances.[1−3] The lithology of such reservoirs mainly consists of tight sandstone, tight limestone, and carbonate rocks, and the average permeability of the pressure matrix in the overlying rocks is less than 0.1 mD (although some experts consider the average value to be 0.2 mD).[4] Since the large-scale development of the Bakken tight oil reservoir in 2008, tight oil exploration and development has become a hot field in oil and gas exploration and development.[5] In April 2013, the United States Geological Survey reassessed the Bakken and Three Forks tight oil resources as approximately 10×10^8 t. In December 2018, the tight oil production in the United States of America was about 7 million barrels per day. According to the results of the fourth oil and gas resource evaluation conducted by the China National Petroleum Corporation, the recoverable amount of tight oil resources in the major oil-bearing basins in China is 13×10^8 t, which indicates great development potential.[6,7] By 2019, the Daqing oilfield T21-4 tight oil demonstration zone had an annual output of 31,000 t of crude oil. In 2021, the tight oil block of the Daqing Gaohua Oilfield (Aonanmao 2 block) had accumulated an additional 656.6 tons of crude oil. Hydraulic fracturing network cores were first extracted from the Mahu Oilfield in Xinjiang, which provided a "golden key" for tight oil development. In the Dagang Oilfield, the production of tight oil

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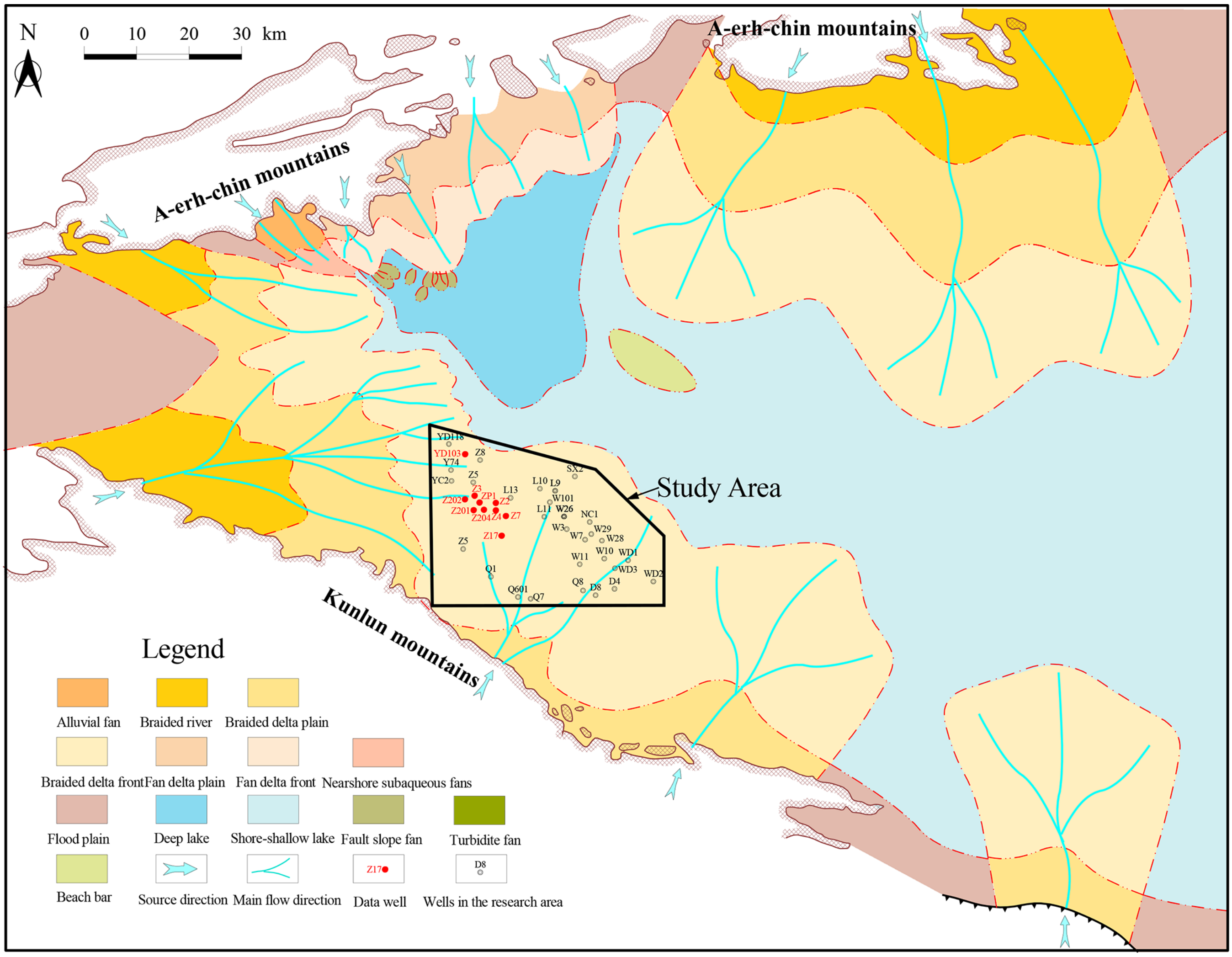


Figure 1. Location of the Zhahaquan area in the Qaidam Basin (modified by Dinghong, Yanxiong et al.).[20,21]

in the old area was effectively increased and stabilized by utilizing the "enhanced energy throughput+" series technology. The Guan106 block achieved an increase of 6726 tons of oil. In 2023, the tight oil of the Tiaohu Formation in Santanghu, Xinjiang, was preliminarily evaluated, and the geological resource amount was estimated as 1.43×10^8 t, with a proven geological oil reserve of 3698×10^4 t.[8] The tight oil exploration and development in China have shown that tight oil will infuse new growth into China's oil and gas reserves and production. The tight oil resources in China have five distinct characteristics: large expanse of tight reservoirs (porosity <10%, matrix overburden permeability $K < 0.1$ mD, and pore throat DRT <1 μm) and a set of high-quality mature hydrocarbon source rocks (I- or II-type kerogen, average total organic carbon (TOC) > 1%, Ro = 0.6%−1.3%). Tight reservoirs with continuous distributions are in close contact with source rocks, without any obvious trap boundaries. The American Petroleum Institute (API) density of crude oil in a tight reservoir is greater than 40° or less than 0.8251 g/cm^3. Crude oil is light[3,9] and is produced from tight low-porosity, low-permeability reservoirs.

The Qaidam Basin is located in the hinterland of Eurasia, at the northern foot of the Qinghai−Tibet plateau. It is located at an altitude of 2600−3000 m and covers an area of about 12.1×10^4 km^2.[10] In the Triassic, the Qaidam Basin entered the continental basin evolution stage, and Paleozoic, Mesozoic, and Cenozoic sedimentary strata developed in this basin.[11] The tectonic units in the basin are the Chaixi uplift, the Yiliping depression, the Sanhu depression, and the Chaibei margin uplift.[12] The Zhahaquan area is located in the Kunbei fault step zone in the Chaixi uplift.[13] The Zhahaquan area has two main groups of faults—the first is the NW fault and the other is the Alar fault and the Zhahaquan fault.[14,15]

The Zhahaquan exploration area is the first 100-million-ton tight oil reserve area considered for exploration in the Qinghai Oilfield.[16,17] During the sedimentary period of the Neogene Upper Ganchaigou Formation (N1) in the Zhahaquan area, a set of source rocks of semideep lake and deep lacustrine facies and a set of thin, interbedded fine sandstone and argillaceous limestone were deposited, providing favorable conditions for the formation of tight oil. This area has 12 exploration wells, among which industrial oil flow has been obtained in seven wells. In fact, the daily crude oil output of the Z7 well is 50 m^3, and this motivated the expansion of the exploration field of clastic rocks in southwest Qaidam and led to the discovery of packaged tight oil reservoirs with high natural production and large reserves of single wells in China. This is another major breakthrough in China's tight oil following the discovery of the Ordos Basin, the Songliao Basin, and the Xinjiang Oilfield and has opened a new avenue of tight oil exploration and development in the Qaidam Basin.[18,19] The first single-block 50,000 ton production capacity

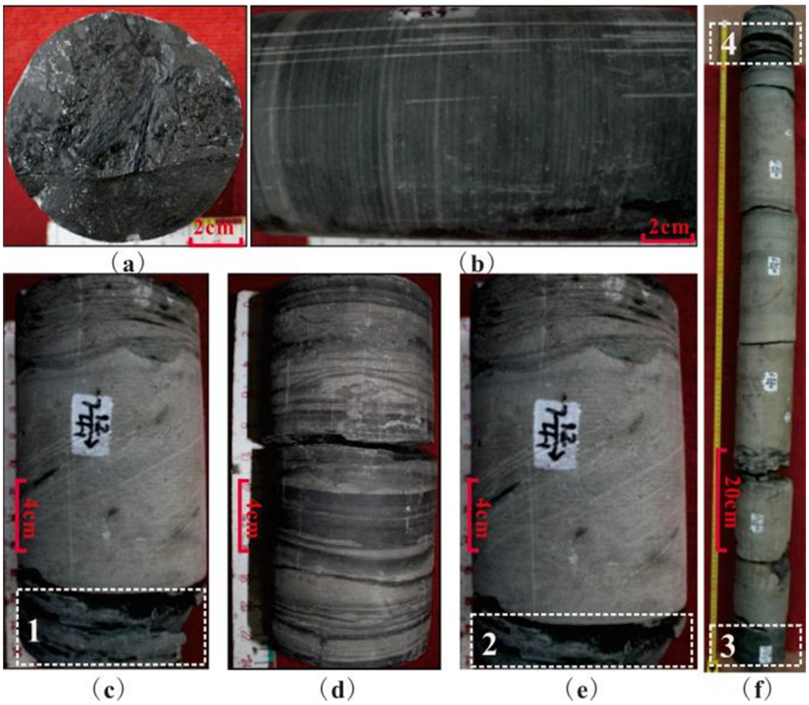


Figure 2. Core photos. (a) Well name: ZP1; depth: 3291.5 m; plant debris. (b) Well name: ZP1; depth: 3293.7 m; gray mudstone. (c) Well name: ZP1; depth: 3296.8 m; Member 1 is the source rock. (d) Well name: ZP1; depth: 3264.3 m; thin interbedded sandstone and mudstone. (e) Well name: Z1; depth: 3264.3 m; member 2 is the source rock. (f) Well name: ZP1; depth: 3289.6−3290.1 m; Members 3 and 4 are the source rocks.

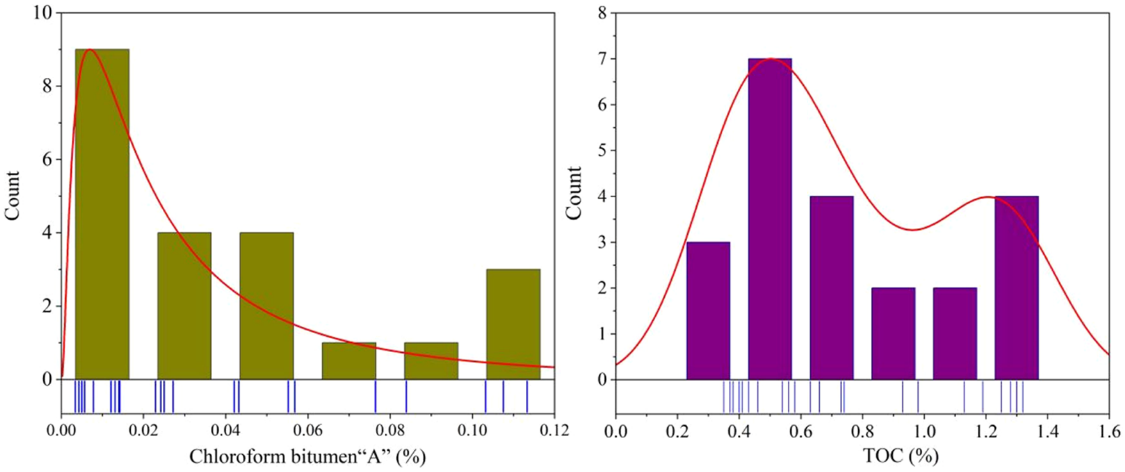


Figure 3. Distribution characteristics of chloroform bitumen "A" and total organic carbon (TOC).

Table 1. Evaluation Criteria of Organic Matter Abundance of Tertiary Saltwater Lacustrine Source Rocks in the Western Part of Southern Qaidam Basin, China[22]

	organic matter abundance parameter			
quality of source rock	total organic carbon (%)	chloroform bitumen "A"/%	total hydrocarbon ($mg{\cdot}L^{-1}$)	potential hydrocarbon generation amount ($mg{\cdot}g^{-1}$)
high-quality source rock	>1.0	>0.15	>750	>6.0
good source rocks	0.8−1.0	0.10−0.15	500−750	4.0−6.0
medium-quality source rock	0.6−0.8	0.05−0.10	200−500	2.0−4.0
poor-quality source rock	0.4−0.6	0.015−0.05	100−200	0.5−2.0
not source rocks	<0.4	<0.015	<100	<0.5

base of the Qinghai Oilfield was built in the Zhahaquan area. This production base has a production capacity completion rate of 92% and a cumulative production of over 200,000 tons of crude oil. The Zhahaquan area has become the main hotspot for the exploration of lithologic oil reservoirs in the Qinghai Oilfield. Wells Z2, Z7, Z11, and Z3 were discovered in the slope area. Vertically, four sets of oil-bearing series have been identified. However, the exploration and development level of the Neogene

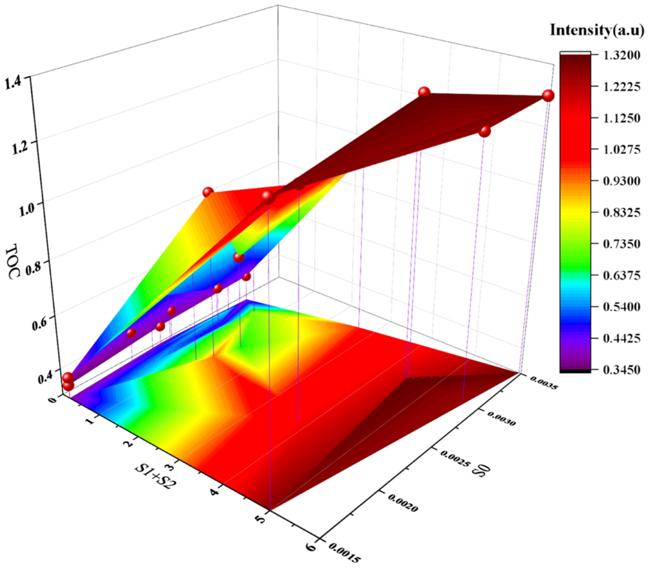


Figure 4. Relationship between TOC and potential hydrocarbon generation in the lower Neogene Upper Ganchaigou Formation (N1) source rock in the Zhahaquan area.

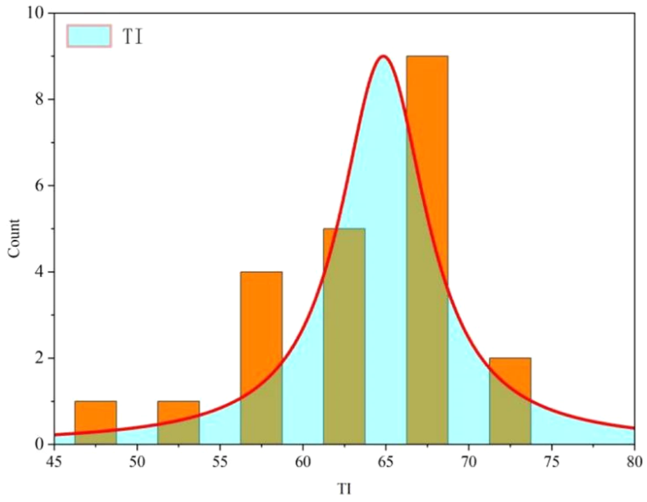


Figure 5. Distribution characteristics of source rock type index (TI).

Upper Ganchaigou Formation (N1) in the Zhahaquan area is relatively low, and there is an urgent requirement to conduct in-depth research on the geological characteristics of this formation. The reserve area can be further expanded, and the oil-bearing series further enriched based on the analysis of the geochemical characteristics of the tight oil in N1 combined with the production test results of typical wells (Figure 1). This work not only provides a detailed evaluation of the exploration and development potential of N1 in Zhahaquan but also provides a scientific basis for the fine exploration of oil and gas in the southwestern Qaidam Basin. These results are of great significance for the search for high-quality oil replacement resources and to ensure a steady increase in the reserves and production in the Qinghai Oilfield. The location of the study area is shown in Figure 1.

2. EXPERIMENTAL SECTION

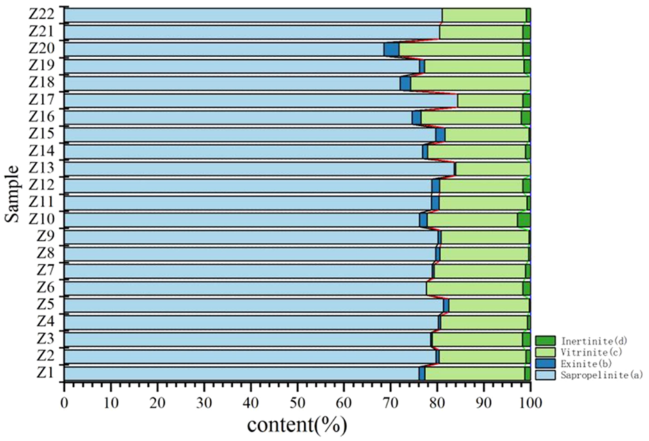


Figure 6. Distribution characteristics of kerogen components.

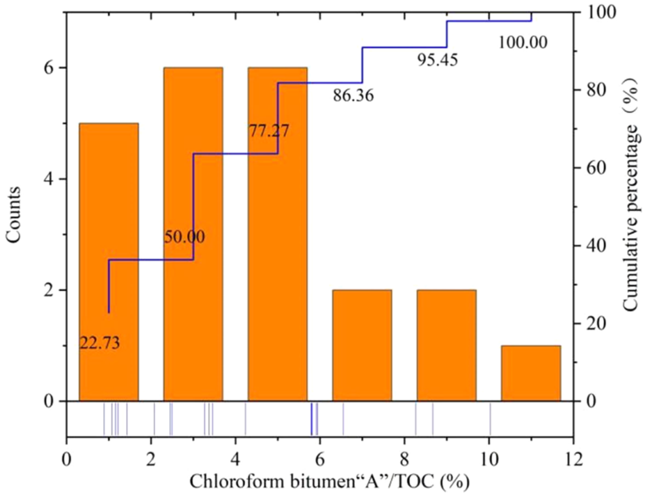


Figure 7. Distribution characteristics of chloroform bitumen "A"/TOC.

In this study, the source rock samples in N1 were analyzed. Twenty-two samples were collected, each weighing 100 g. The samples were pulverized to 80 meshes to prepare for Rock−Eval pyrolysis and TOC evaluation. A Rock-Eval instrument (YQ-VIIA) was used to perform the pyrolysis analysis to obtain the parameters T_{max} (peak cracking hydrogen temperature), S_0 (gaseous hydrocarbon content), S_1 (liquid hydrocarbon content), and S_2 (cracking hydrocarbon content). S_0 was measured at a constant temperature of 90 °C maintained for 2 min. S_1 was measured after rapid heating to 300 °C and then maintaining a constant temperature for 3 min. S_2 was obtained after heating to 600 °C at the rate of 50 °C/min and then keeping the temperature constant for 1 min. The TOC content in rock samples was determined by using a CS230 analyzer. The vitrinite reflectivity (Ro) was measured by a microphotometer at a temperature of 23 °C and a humidity of 50%. Each sample had 30 data testing points.

The content of chloroform bitumen "A" in source rocks was determined using a YS/B automatic multifunction extraction instrument. The experimental procedure of saturated hydrocarbon separation and mass spectrometry is as follows. The samples (100 g) were dried in vacuum at 50 °C and were ground to 150 mesh size (particle size: ~0.1 mm); subsequently, chloroform Soxhlet extraction was performed for 72 h to obtain chloroform bitumen "A." After chloroform bitumen was precipitated, the saturated hydrocarbon, aromatic hydrocarbon,

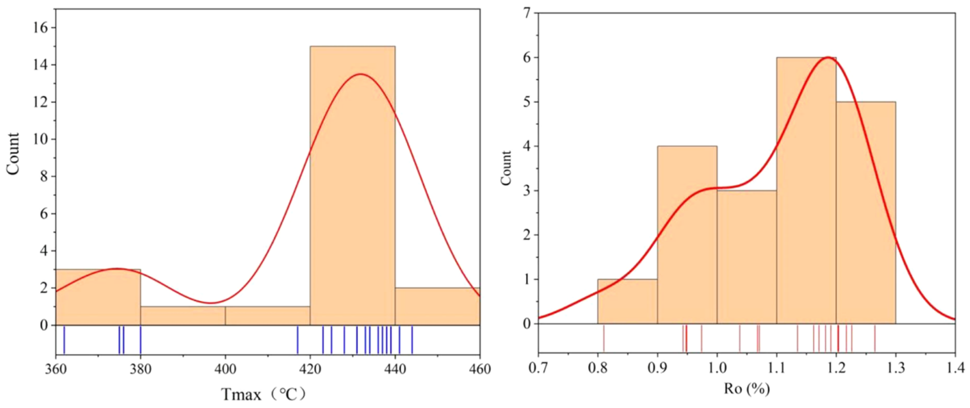


Figure 8. Distribution characteristics of cracking hydrocarbon peak temperature (T_{max}) and vitrinite reflectance (Ro).

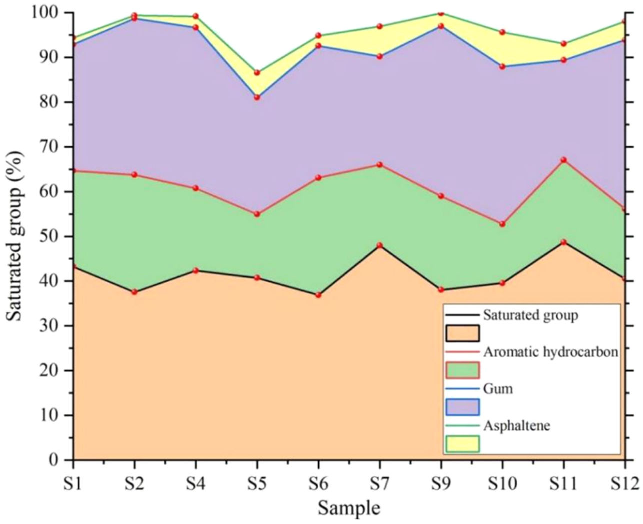


Figure 9. Component analysis results: statistics.

and colloidal components were eluted successively on an alumina−silica gel column by using hexane, dichloromethane−hexane (volume ratio 3:1), and dichloromethane−methyl alcohol (volume ratio 2:1). The saturated hydrocarbon components of chloroform bitumen "A" were used for gas chromatography−mass spectrometry (GC-MS) analysis. A ThermoFisher-DSQII chromatography−mass spectrum analyzer was used for aromatic component analysis. The chromatographic column was a DB-5MS (60 m × 0.32 mm × 0.25 μm) elastic quartz capillary column. The heating process of the saturated hydrocarbon was as follows: first, the sample was heated to 80 °C and then maintained at a constant temperature for 4 min; then, it was heated at the rate of 4 °C/min to 295 °C and maintained at a constant temperature for 30 min. The heating procedure of the aromatic components was as follows: first, the sample was heated to 80 °C and maintained at a constant temperature for 4 min; subsequently, it was heated at the rate of 3 °C/min to 290 °C and maintained at a constant temperature for 15 min. The conditions for mass spectrum analysis were as follows: the electron ionization source was at 70 eV; the ion source temperature was 250 °C; He was the carrier gas; the inlet temperature was 290 °C; and the transmission line temperature was 280 °C. The core photos of the target strata in the study area are shown in Figure 2.

In the physical property analysis of the reservoir, thin sections of rocks were identified using a ZEISS imager instrument and an A1 polarizing microscope. Scanning electron microscopy analysis was performed using a ZEISS EVO-18 electron scanning microscope. The cast thin sections were analyzed using the ZEISS imager and an A2 polarizing microscope.

3. RESULTS AND DISCUSSION

The TOC distribution of source rocks of N1 in the Zhahaquan area was from 0.35 to 1.32%, with an average value of 0.75% (Figure 3). According to the evaluation standard of the organic matter abundance of tertiary lacustrine source rocks in the western southern region of the Qaidam Basin (Table 1), the organic matter abundance of source rocks in the N1 Formation of the Zhahaquan area, which is a good source rock for oil exploration, is moderate.

Rock pyrolysis is a common method for evaluating oil and gas resources and classifying organic matter. The distribution range of $S_1 + S_2$ is 0.048−5.95 mg/g. According to the relationship between the measured TOC and $S_1 + S_2$ (Figure 4), the TOC of the source rock is positively correlated with the hydrocarbon generation potential. When TOC >0.6%, the hydrocarbon generation potential of the source rock increases drastically; this behavior is consistent with the characteristics of the hydrocarbon generation capacity of the Qaidam Basin.

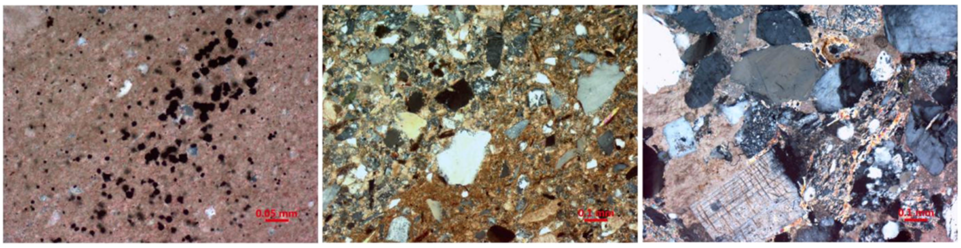
The source rock type index (TI) in the Zhahaquan area is 48.70−72.23, with an average of 63.17 (Figure 5); the average maceral content of the kerogen in the sapropel group is 78.41%. The average vitrinite content was 19.55%, and the exinite and idler group contents were less than 3.0%. The organic matter belonged to the II_1 type (Figure 6). The chloroform bitumen "A" content was 0.0034−0.1133% (Figure 3). The hydrocarbon generation rate of organic matter can reflect the hydrocarbon generation potential of source rocks. The hydrocarbon generation conversion rate is the ratio of chloroform bitumen "A" to the organic carbon content, and this rate can reflect well the hydrocarbon generation conversion efficiency of organic matter. Statistics show that the hydrocarbon generation conversion rates of more than 64% of the source rocks in N1 of the Zhahaquan Area exceeded 3.0%, and hence, they were identified as good source rocks (Figure 7). The Ro values were in the range of 0.810−1.265%, with an average of 1.10% (Figure 8). T_{max} was in the range of 362−444 °C, and the main distribution range was 420−440 °C (Figure 8).

The results of the source rock group analysis (Figure 9) show that the average saturated hydrocarbon content, average aromatic hydrocarbon content, average gum content, and

Table 2. Pyrolytic Parameters of the Neogene Upper Ganchaigou Formation (N1) in the Zhahaquan, Qaidam Basin[a]

sample name	depth (m)	layer	TOC	S_0	S_1	S_2	T_{max}	GPI	OPI	TPI	PG	PC
Z1	3231.7	N_1	1.25	0.0030	0.1516	5.5167	436	0.0005	0.0267	0.0272	5.6713	0.4707
Z2	3238.3	N_1	1.19	0.0030	0.2809	4.1231	431	0.0007	0.0637	0.0644	4.4070	0.3658
Z3	3242.3	N_1	0.73	0.0030	0.0517	0.5674	444	0.0048	0.0831	0.0879	0.6221	0.0516
Z4	3248.9	N_1	0.46	0.0027	0.0575	0.4088	375	0.0058	0.1226	0.1284	0.4690	0.0389
Z5	3251.3	N_1	0.66	0.0026	0.0516	1.2949	441	0.0019	0.0382	0.0401	1.3491	0.1120
Z6	3255.4	N_1	1.32	0.0030	0.1696	4.3136	433	0.0007	0.0378	0.0385	4.4862	0.3724
Z7	3259.7	N_1	0.58	0.0029	0.0272	0.1527	428	0.0159	0.1488	0.1647	0.1828	0.0152
Z8	3263.9	N_1	0.4	0.0031	0.0283	0.1051	425	0.0227	0.2073	0.2300	0.1365	0.0113
Z9	3272.1	N_1	0.98	0.0033	0.1229	2.5161	434	0.0012	0.0465	0.0477	2.6423	0.2193
Z10	3278.9	N_1	0.63	0.0028	0.0184	0.1237	428	0.0193	0.1270	0.1463	0.1449	0.0120
Z11	3283.5	N_1	0.93	0.0024	0.0464	1.1520	439	0.0020	0.0386	0.0406	1.2008	0.0997
Z12	3284.7	N_1	1.28	0.0015	0.2365	4.7773	423	0.0003	0.0472	0.0475	5.0153	0.4163
Z13	3287.5	N_1	0.38	0.0015	0.0217	0.1804	376	0.0074	0.1066	0.1140	0.2036	0.0169
Z14	3299.0	N_1	0.43	0.0020	0.0238	0.1998	380	0.0089	0.1055	0.1144	0.2256	0.0187
Z15	3300.3	N_1	0.35	0.0015	0.0218	0.1699	362	0.0078	0.1128	0.1206	0.1932	0.0160
Z16	3301.1	N_1	0.56	0.0021	0.0247	0.4581	437	0.0043	0.0509	0.0552	0.4849	0.0402
Z17	3301.3	N_1	0.74	0.0023	0.0535	0.9637	437	0.0023	0.0525	0.0548	1.0195	0.0846
Z18	3311.0	N_1	0.37	0.0023	0.0122	0.0362	423	0.0454	0.2406	0.2860	0.0507	0.0042
Z19	3314.5	N_1	0.41	0.0024	0.0140	0.0345	417	0.0472	0.2750	0.3222	0.0509	0.0042
Z20	3237.6	N_1	1.3	0.0035	0.3373	5.6221	428	0.0006	0.0566	0.0572	5.9629	0.4949
Z21	3238.5	N_1	1.13	0.0022	0.2525	3.5568	428	0.0006	0.0662	0.0668	3.8115	0.3164
Z22	3241.7	N_1	0.54	0.0023	0.0275	0.3002	438	0.0070	0.0833	0.0903	0.3300	0.0274

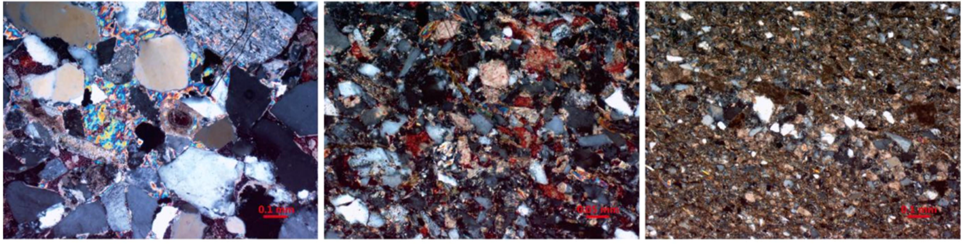
[a] Note: S_0, gaseous hydrocarbon content; S_1, liquid hydrocarbon content; S_2, cracking hydrocarbon content; T_{max}, cracking hydrocarbon peak temperature; GPI, gas yield index; OPI, oil yield index; TPI, total yield index; PG, potential hydrocarbon generation amount; PC, effective carbon content; TOC, total organic carbon.



ZP1 3235.70 (+) ×200
Micrite

Zp1 3233.06 (+) ×100
Fine grained feldspar sandstone

Zp1 3233.56 (+) ×100
Fine grained lithic feldspar sandstone



ZP1 3254.47m (+) ×100
Gray-bearing medium-fine
feldspar sandstone

ZP1 3258.85m (+) ×200
Siltstone bearing ash

ZP1 3264.50m (+) ×100
Siltstone bearing ash

Figure 10. Reservoir rock types in the study area.

average asphaltic content were 41.5%, 19.25%, 31.22%, and 3.76%, respectively.

According to the comprehensive parameters, the organic matter types of the source rocks of N1 in the Zhahaquan area were good for oil exploration; the organic matter abundance was moderate, the textural maturity was high, and it entered the hydrocarbon generation threshold, which is in the peak oil-generation stage. This stage is conducive to the formation of oil and gas. Table 2 provides a statistical table of rock pyrolysis parameters.

The petrographic characteristics of reservoirs in the study area showed that the lower member of N1 in the Zhahaquan area was mainly composed of micrite, fine-grained feldspar sandstone, fine-grained feldspar sandstone, and other lithologies (Figure 10). X-ray diffraction analysis results of all minerals revealed the following composition: quartz (average 37.8%), potash feldspar (average 5.59%), soda feldspar (average 19.7%), and calcite (average 13.0%); the average clay mineral content was 11.5%. Some samples contained dolomite, calcite, karstenite, and ferrodolomite (Figure 11).

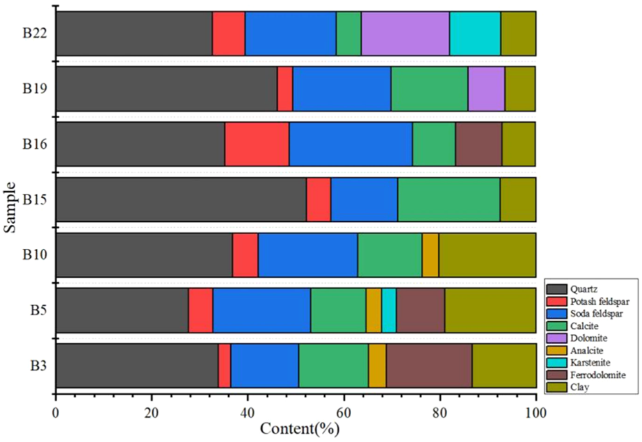


Figure 11. X-ray diffraction analysis results.

A closed coring analysis was conducted for the CZ1 well. The results showed that the average porosity, permeability, oil saturation, and water saturation were 8.0%, 0.861 × 10^{-3} μm^2, 30.0%, and 21.6%, respectively (Table 3). The results of conventional slice and cast slice analyses showed that the reservoir had mainly intergranular pores and dissolution pores, and microfractures were visible. The results of nuclear magnetic resonance (NMR) analysis showed that the T2 spectra were bimodal, indicating both intergranular pores and micropores formed by clay minerals (Figure 12).

Exploration wells play a very important role in oil and gas exploration, and core logging, geophysical logging, and production testing data obtained from these wells have led to much development in this field. A comprehensive analysis of the source rock and reservoir of the exploration well can help determine the hydrocarbon generation potential of the source rock and physical properties of the reservoir, including brittleness and other parameters, thereby laying a foundation for the integrated development of geology and engineering. Meanwhile, based on the analysis results of exploration wells, the reserve range can be determined. For example, using data from wells Z2, Z7, Z11, and Z3, a comprehensive analysis was conducted, and four oil zones and four sets of oil-bearing formations were identified. Evaluation well Z215 in the southern part of the Z7 well area achieved a high production, and the reserve area of well Z7 was expanded by exploring the oil-bearing boundaries. A comprehensive analysis was conducted on well Z17, and based on these results, a cumulative oil production of 168 tons was achieved. In the initial stage of trial production, the daily average oil production reached 10.5 tons. Thus, new lithological oil and gas reservoirs are being discovered in the Zhahaquan area of the Qinghai Oilfield, and the exploration is being expanded.

Based on the parameters of the source rocks, it is concluded that the source rocks in the Zhahaquan area are medium−good source rocks and have good potential for shale oil exploration and development. The oil test results of YD103 and seven other wells show that the daily oil index per meter ranges from 0.38 to 6.5 $m^3/d \cdot m$ (Table 4), indicating that the source rocks have the ability to form industrial oil. Taking Well Z3 as an example, the source rock is interbedded with sand mudstone and argillaceous limestone reservoirs in a thin interbedded distribution. The source rock has 17 layers with a thickness of 0.38−2.2 m and a cumulative thickness of 17.43 m. The oil test result of 3242.0−3251.0 m is 12.36 t/d, which is the oil layer (Figure 13). It further indicates that the Zhahaquan area has great potential for tight oil exploration and development.

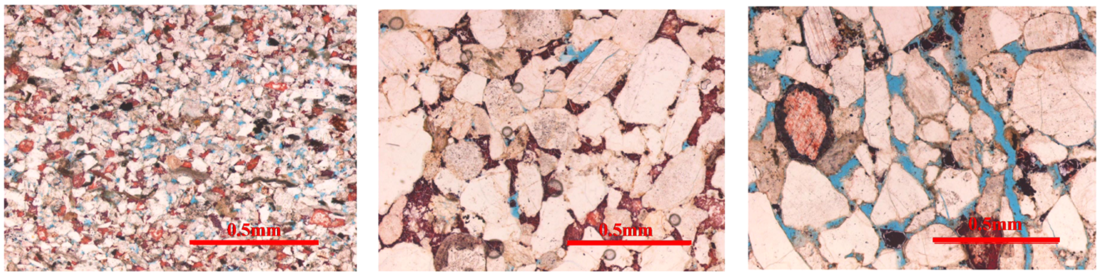
4. CONCLUSIONS

We investigated the geochemical properties of source rocks and reservoirs in the Neogene Upper Ganchaigou Formation (N1) in the Zhahaquan area, Qaidam Basin. The results indicated that the source rock of N1 had a strong hydrocarbon generation capacity, and the reservoir had a good reservoir performance. The source rock and reservoir are distributed in an interbedded

Table 3. Statistical Table of Reservoir Physical Properties and Oil-Bearing Analysis Results[a]

sample number	depth (m)	porosity (%)	permeability (10^{-3} μm^2)	rock density (g/cm^3)	oil saturation (%)	water saturation (%)
1	3239.00−3247.00	7.6	0.36	2.752	55.1	22.7
2	3239.00−3247.00	5.0	<0.02	2.741	50.4	20.3
3	3239.00−3247.00	5.8	0.042	2.712	41.2	8.6
4	3239.00−3247.00	6.3	4.180	2.674	21.7	18.4
5	3239.00−3247.00	4.0	0.190	2.655	36.0	12.7
6	3239.00−3247.00	5.9	0.300	2.661	13.9	22.4
7	3239.00−3247.00	7.0	0.260	2.659	31.7	7.0
8	3239.00−3247.00	5.2	0.170	2.667	39.4	16.1
9	3239.00−3247.00	8.5	0.400	2.673	19.5	11.4
10	3239.00−3247.00	4.4	0.028	2.686	26.7	30.4
11	3239.00−3247.00	14.3	0.025	2.682	16.6	3.4
12	3247.00−3255.00	6.9	0.340	2.681	67.9	2.5
13	3247.00−3255.00	8.8	0.230	2.676	44.8	7.6
14	3247.00−3255.00	9.9	7.990	2.682	22.5	28.4
15	3247.00−3255.00	8.2	0.100	2.688	31.9	31.0
16	3247.00−3255.00	12.4	0.740	2.676	29.9	15.9
17	3247.00−3255.00	10.5	0.140	2.691	6.4	45.3
18	3247.00−3255.00	10.6	0.150	2.688	19.4	29.5
19	3247.00−3255.00	9.8	0.077	2.687	12.6	41.8
20	3247.00−3255.00	7.4	0.042	2.693	23.2	58.9
21	3273.00−3280.24	9.7	1.470	2.678	19.9	19.4

[a] Note: When calculating the saturation, the density of water was 1.0100 g/ml and the oil density was 0.8750 g/ml.



ZP1 3247.0m (-) X100
Intergranular pore

ZP1 3239.0m (-) X100
Corrosion pore

ZP1 3273.0m (-) X100
Microfracture

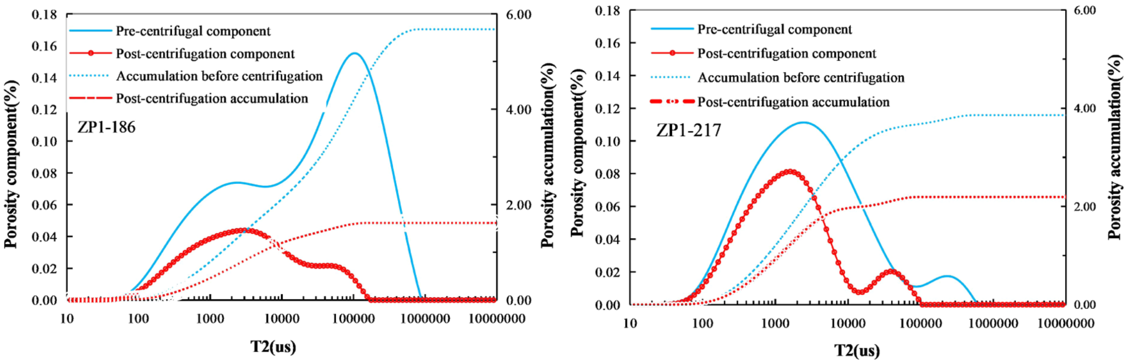


Figure 12. Reservoir pore types and nuclear magnetic resonance (NMR) T2 spectral characteristics.

Table 4. Statistical Table of Oil Test Results in the Zhahaquan Area

well name	oil production methods	daily production (m^3) oil	gas	water	test production measure	top depth (m)	bottom depth (m)	test conclusion	daily oil production per meter (PI)
YD103	Swab for production	3.85	0	0	conventional SWB	2486	2488	oil layer	1.93
Z2	Φ4 mm (oil nipple)	4.16	minor	0	regular discharge	3292.5	3303.5	oil layer	0.38
	Swab for production	8.16	minor	0	conventional SWB				0.74
	Φ4 mm (oil nipple)	17.35	0	0	after the pressure choke				1.58
Z3	Swab for production	5.01	0	0	conventional SWB	3242	3251	oil layer	0.56
	Φ4 mm (oil nipple)	17.73	0	0	after the pressure choke				1.97
	Swab for production	5.98	0	0	conventional SWB	3185.5	3188.5	oil layer	1.99
Z4	Swab for production	5.14	0	0	conventional SWB	3243	3245	oil layer	2.57
Z7	Φ4 mm (oil nipple)	52.02	0	1.43	conventional SWB	3510	3518	oil layer	6.50
Z201	Swab for production	2.24	0	0	conventional SWB	3452	3456	oil layer	0.56
	Swab for production	22.09	0	0	after the pressure choke				2.45
	Swab for production	6.15	0	0	conventional SWB	3269	3276	oil layer	0.88
Z202	Swab for production	7.91	0	0	conventional SWB	3114	3119	oil layer	1.58
Z204	Φ4 mm (oil nipple)	13.3	0	0	regular discharge	3517	3531	oil layer	0.95

manner, which provides a very favorable condition for the formation of tight oil. The main conclusions of this study are summarized as follows:

(1) The hydrocarbon source rock organic matter type in the Zhahaquan area was II_1, the TOC was 0.32−1.32%, the TI was 48.70−72.23, the chloroform bitumen "A" content was 0.0034%−0.1133%, the Ro was 0.810%−1.265%, T_{max} was distributed at 362−444 °C, and the hydrocarbon generation conversion rate was 0.89%−10.0%. The source rocks in the study area are the better hydrocarbon source rocks and have entered the stage of hydrocarbon generation threshold and peak in the source. The strong hydrocarbon-generating ability of the source rock provides an important material basis for the formation of tight oil in the study area.

(2) The reservoir type in the study area is a tight clastic rock reservoir, the pores of the reservoir are mainly

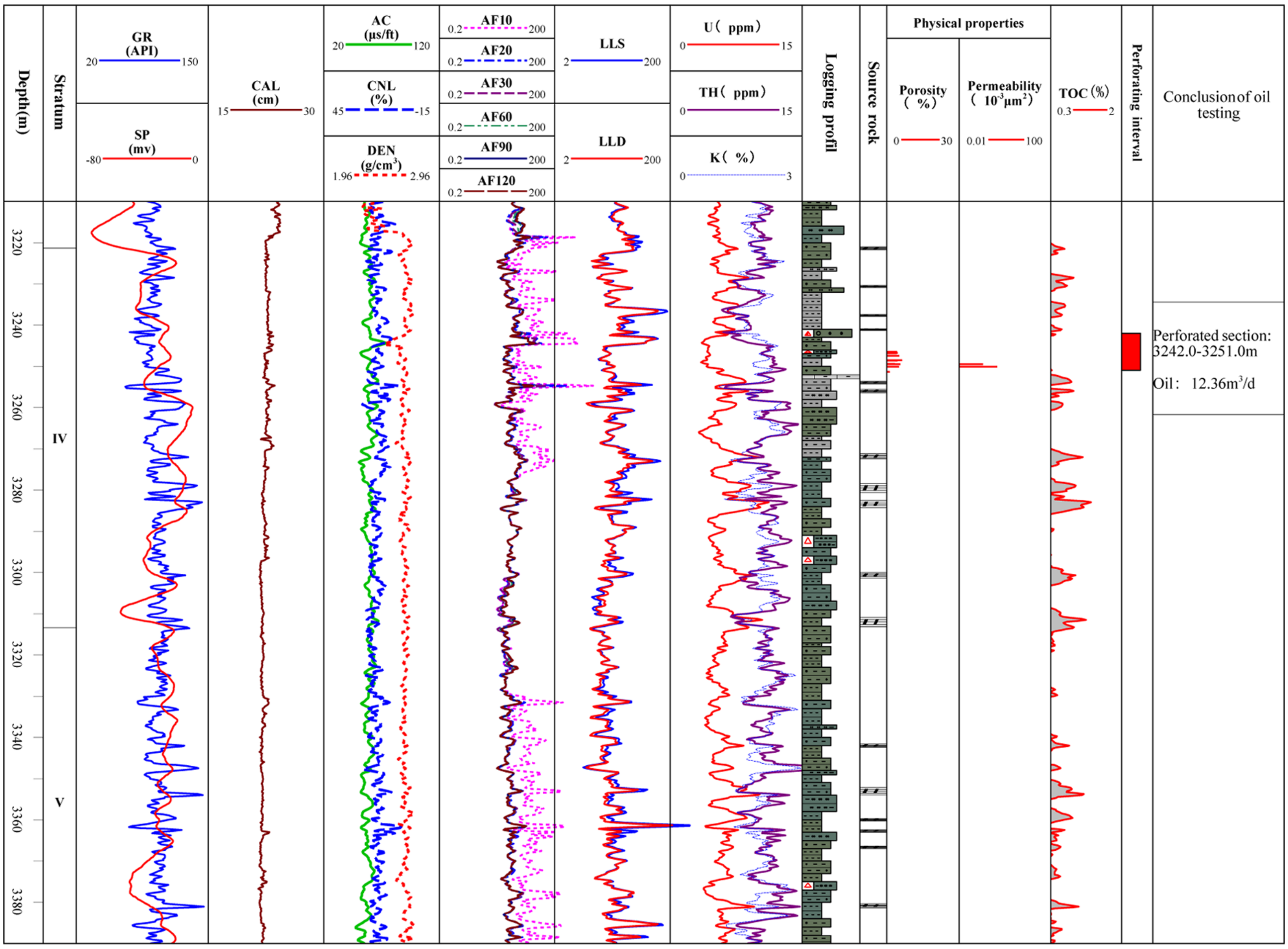


Figure 13. Comprehensive logging interpretation results of Well Z3.

intergranular pores, dissolution pores, and microfractures. The average porosity is 8.0%, the average permeability is $0.861 \times 10^{-3}\ \mu m^2$, the average oil saturation is 30.0%, and the average water saturation is 21.6%. Interbedded distribution of the reservoir and the source rock is one of the key factors for tight oil enrichment in the study area.

(3) Comprehensive analysis of the source rock and reservoir of the exploration well can determine the hydrocarbon generation potential of the source rock, the physical property of the reservoir, brittleness, and other parameters, laying a foundation for the integrated development of geology and engineering. Meanwhile, based on the analysis results of exploration wells, the reserve range can be further determined. The daily oil index per meter for wells YD103, Z2, Z3, Z4, Z7, Z201, Z202, and Z204 ranged from 0.38 to 6.5 m^3/d·m, indicating that the source rocks in the study area were capable of forming industrial oil and gas. The results of the single-well oil test further indicated that the Zhahaquan area has a huge potential for tight oil exploration and development. The analysis of the geochemical characteristics of source rocks and the study of reservoir geological characteristics will provide theoretical support and reference for tight oil exploration and development in this area.

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Notes

The authors declare no competing financial interest.

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