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Research Article

Research on Application of Microbial Exploration Technology Based on Abnormal Index System

Zhihua Yuan[1,2] and Yuqing Zhang[1]

[1]*Key Laboratory of Exploration Technologies for Oil and Gas Resources, Yangtze University, Ministry of Education, Wuhan, Hubei 430100, China*
[2]*Institute of Mud Logging Technology and Engineering, Yangtze University, Jingzhou, Hubei 434023, China*

Correspondence should be addressed to Yuqing Zhang; hh17222@163.com

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MPOG (microbial prospecting of oil and gas) technology has its unique advantages, and the microbial anomaly index system lays the basis for comprehensive evaluation of MPOG data and prospect prediction of target areas. In view of the problem that the current exploration technology is limited in the areas where seismic exploration is difficult to reach or difficult to implement, this article uses modern biotechnology to discuss the technical mechanism of microbial exploration technology and the indicators of abnormal technology system in detail, on the basis of known oil and gas properties of completed wells. In order to establish a reference system suitable for the actual geological characteristics of oilfields, and to further improve the index system for identifying oil and gas microbial abnormalities in oil and gas areas, specific microbial abnormal indicators are isolated, cultivated, and detected. Combining the geological characteristics of the work area, drilling and oil testing data, and classification evaluation of oil and gas-bearing areas, as well as oil and gas prospects, is performed. MPOG technology has a certain applicability in the evaluation of oil and gas properties. The research in this article can provide a favorable reference for the selection of favorable oil and gas zones and well location deployment.

1. Introduction

The rapid development of modern biotechnology has been widely applied into various fields of science and economy and has also greatly promoted the development of oil and gas microbial exploration technology [1, 2]. The scarcity of resources and energy shortages increases the risks and costs of traditional exploration. The promotion and application of effective microbial exploration technology provide a good opportunity [3]. As a new oil and gas reservoir evaluation technology, MPOG technology was developed by geological microbiologists and geochemists. After more than 60 years of tortuous development, MPOG technology has finally received tremendous attention from global oil and gas experts due to its advantages of directness, effectiveness, low polysilicon, and economy [4, 5]. After more than 50 years of exploration, most of the oil and gas-bearing basins in China have been explored to a high degree, and a large number of easy-to-discover oil and gas fields have been found. However, with the in-depth development of exploration, the distribution of remaining oil and gas resources is scattered, the scale of oil and gas reservoirs is small, and there are many nonstructural oil and gas reservoirs, which makes conventional exploration more difficult and expensive. Therefore, the application of MPOG technology is of great significance for predicting unconventional oil and gas reservoirs and deep oil and gas reservoirs [6, 7], determining the oil-bearing grade and oil-gas distribution of geological structures, and indicating the location of oil and gas reservoirs [8]. As a result, MPOG technology is of great significance for improving the benefits of oil and gas exploration and development in China.

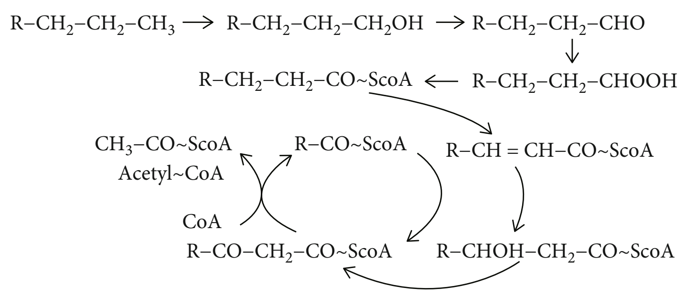

Figure 1: Degradation of *n*-alkanes to acetyl-CoA by β- oxidation.

2. Principles and Methods of Microbial Exploration Technology

2.1. Microbiological Basis of MPOG. The high adaptability and widespread distribution of bacteria towards different nutrient sources is the basis for microbial exploration. Like other types of bacteria, hydrocarbon oxidizing bacteria are distributed worldwide [9, 10]. The bacteria were detected in sediment samples from the North Sea and the Barents Sea, soil samples from Northern Europe, samples from (Oman) deserts and salt deserts, samples from arid grasslands in Australia, and samples from permafrost soils. Wherever life exists, as long as traces of hydrocarbons exist in the soil, such obligate bacteria are clearly proliferating. This obligation has the potential to allow bacteria to exhibit different population distributions in accordance with their own biochemical properties [11, 12]. There are two categories of bacteria with microbial exploration, including hydrocarbon oxidizing bacteria, and methanotrophic bacteria.

Another type of microbial population utilizes short-chain hydrocarbons (C2-C8) as energy sources. These microorganisms cannot metabolize methane, but short-chain hydrocarbons, such as ethane, propane, and butane, can be utilized by a large number of bacteria (Mycobacteria, Flavobacteria, Nocardia, Pseudomonas). In this process, the number of bacterial species that can utilize such hydrocarbons increases linearly with increasing alkane chain length [13, 14]. The degradation of alkanes firstly carries out terminal oxidation of alkanes by monooxygenase and then further degrades alkanes to acetyl-CoA by β-oxidation, which is the precursor of a large number of biochemical reactions (see Figure 1).

However, in contrast to methane, hydrocarbons do not represent a single species, which contains rich content of polysaccharides and monosaccharides (cellulose, glucose). Even though such bacteria are not present in the natural environment (soil samples), they can survive on short-chain hydrocarbons under laboratory conditions. The detection of bacteria oxidizing n-alkanes of length C_2-C_8 without any acclimation period can indicate the presence of too short-chain hydrocarbons in the soil samples studied, which in turn indicates the accumulation of subsurface oil [15, 16]. In those regions where short-chain hydrocarbons and methane are detected in this way, depending on the strength of the signal, thermogenic gas reservoirs or reservoirs with gas caps containing large amounts of short-chain hydrocarbons can be inferred.

The fact that the cellular content and activity of hydrocarbon oxidizing bacteria (HCOs) in soil and sediment samples is relatively low (comparing with the other physiological groups of bacteria) makes it possible to use the MPOG method to detect oil and gas reservoirs [17, 18]. Depending on ecological conditions and enumeration steps (using fluorescence techniques, detection by nucleic acid analysis), the range spans 103 to 106 cells per gram. Meanwhile, in extreme areas such as swamps, methanotrophs can reach 106 cells per gram. The content of live bacteria in soil samples can also be determined using other techniques. The number of colony-forming units (CFU) formed on solid media and the maximum possible number (MPN) method in nutrient solutions can be used to determine the number of viable bacteria in soil samples [19, 20]. In samples taken from the above oil and gas reservoirs, the cell counts of methane and hydrocarbon oxidizing bacteria were quite high, ranging from 104 to 106 cells per gram.

HCO can be determined using a variety of biochemical and microbiological assays, and a comprehensive research effort has culminated in the development of an assay procedure. The influence of ecological parameters (temperature, seasonal variation, humidity, salinity, pH), other microorganisms (especially sulfate-reducing bacteria in sediments), and biogenic methane can be evaluated.

2.2. Technical Mechanism of MPOG. Driven by the pressure of the oil and gas reservoir, the light hydrocarbon gas in the oil and gas reservoir continuously diffuses and migrates vertically to surface, and the obligate microorganisms in the soil use the light hydrocarbon gas as their only energy source [21, 22]. Microbial anomalies are well developed and formed in the surface soil directly above the reservoir. Using modern biotechnology to isolate, culture, and detect obligate microbial abnormalities, combined with the geological, drilling, oil testing, and other data of the work area, it is possible to carry out prediction of oil and gas areas, grading evaluation of oil and gas prospects, analysis of main controlling factors for oil and gas accumulation, and prediction of remaining oil and gas distribution [23]. Also, single well predrilling rapid evaluation, reservoir prediction, and well location deployment can be performed. Thermogenic hydrocarbons formed and trapped in deep structures escape to the surface and

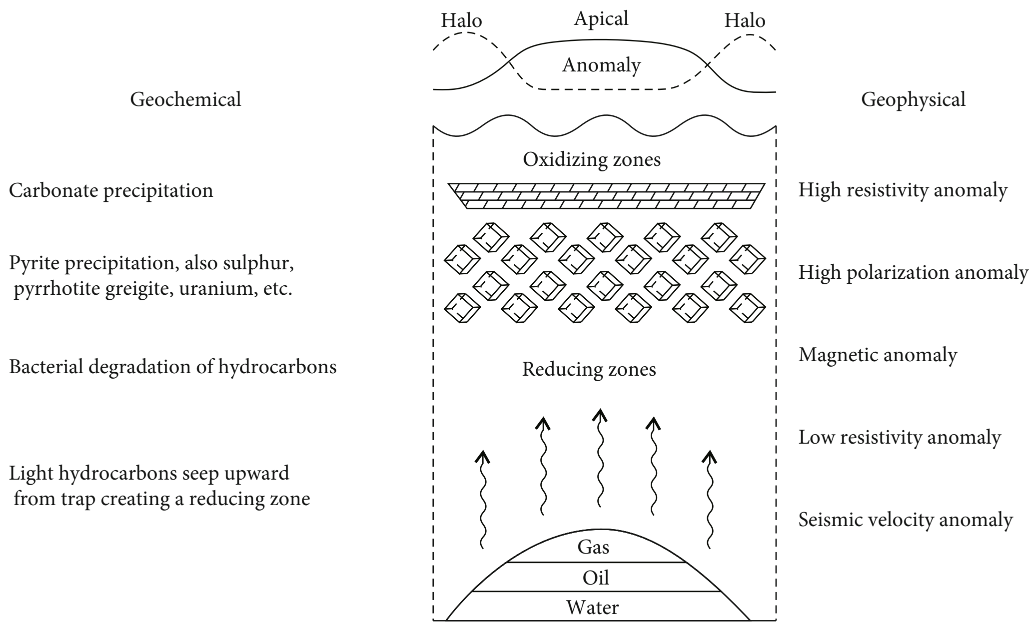

Figure 2: Hydrocarbon micropermeability model and the effect of hydrocarbons on soil and sediment composition.

appear as oil seedlings. However, physical state of hydrocarbons during migration is not well understood, whether the water phase, the dispersed oil phase, or the gas phase migration in the form of solutions or micelles is currently under debate.

The theory of vertical or near-vertical migration of light hydrocarbons from the reservoir to the surface is the basis of MPOG, which has been controversial for many years. However, little attention has been paid to the fact that evidence of vertical migration of light hydrocarbons can also be found in conventional seismic and high-resolution seismic methods. Oil and gas macropermeability is usually associated with faults, and many oil and gas fields have been discovered by drilling wells in leaky zones [24]. If the reservoir cannot be drained by macroseepage, then the smaller microseepage will not drain either. Furthermore, we believe that it is very reasonable that many active underground hydrocarbon source rocks continue to generate and expel hydrocarbons slowly and then recharge to the relevant reservoirs. Thus, the amount of oil in a reservoir is the result of a dynamic balance between recharge rate and losses due to macro- and micropermeability. It is generally believed that the most effective general scientific model for the micropermeability of light hydrocarbons is the vertical upward floating of microbubbles, which is much faster than the horizontal movement of formation water; so, the lateral displacement caused by the movement of formation water is very small.

The best evidence for near-vertical migration of hydrocarbon micropermeability is the light hydrocarbon anomalies frequently detected by geochemists over the years in soil gas and soil, in most cases directly above petroleum deposits. At the same time, the geophysical properties of surface sediments undergo corresponding changes. Therefore, in the process of upward migration of hydrocarbons, geochemical anomalies and geophysical anomalies occur together and are closely related. It is these two types of anomalies that constitute the basic basis of modern oil and gas surface exploration methods (see Figure 2).

Carbon isotope studies also provide strong support for the vertical microseepage migration of hydrocarbons. The soil hydrocarbon gas has the same carbon isotope ratio as the thermogenic gas derived from the underlying sediments and has the same carbon isotope ratio as the surface biogenic gas. Jones and Drozd [25] demonstrated that micropermeable hydrocarbons in surface soils have a good chemical composition correlation with thermogenic hydrocarbons in underlying sediments. These evidences well justify the theory of vertical migration of light hydrocarbons.

The secondary hydrocarbon expulsion of oil and gas is a complex dynamic equilibrium process. A secondary hydrocarbon expulsion model is established on the basis of analyzing the energy dynamics, the physical state of the migration hydrocarbons, their chemical changes during the migration process, and the mechanism of their concentration changes in detail. This model assumes that hydrocarbons migrate as free phases while interacting with heterogeneous rock phases. A possible mechanism for the vertical migration of light hydrocarbon gas from the reservoir to the surface is that the light hydrocarbons pass through an interconnected network of groundwater-filled microfractures. This approach explains why pentane and the higher molecular weight hydrocarbons are absent from the soil gas composition. Because such hydrocarbons are liquid at near-surface temperatures and pressures, the buoyancy is too small to migrate to the surface.

Table 1: Abnormal reference system of microbial oil in Changqing Oilfield.

Classification	Oil display (MU)	Outlier area color
Exception area	>30.00	The red series is filled from light to dark spaced with an oil abnormal value of 5.00
Indeterminate region	25.00~30.00	Yellow fill
Background value area	0.00 to 25.00	White is not filled

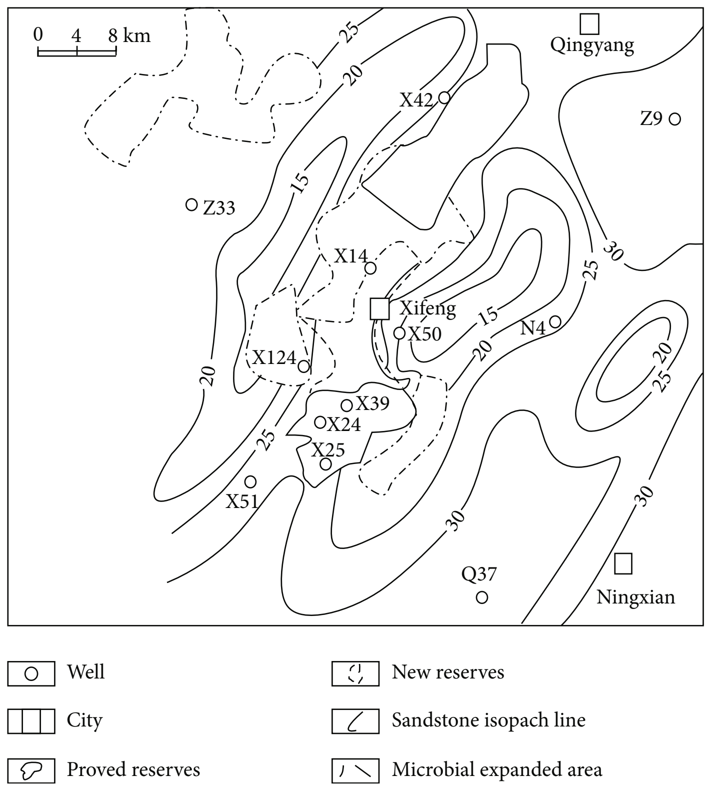

Figure 3: Location map of oil and gas microbial exploration area of Xifeng Oilfield in Changqing.

3. Principles and Methods of Microbial Exploration Technology

3.1. Data Collection. Changqing Oilfield is the first oilfield in China to use microbial exploration technology for exploration and well-location deployment. Based on the first-hand original analysis data obtained in Changqing Oilfield, the surface type, ground height, and various influences such as topography, humidity, lithology, and color have obtained the abnormal value of microbial oil and gas in the Changqing Oilfield work area. The ideal state of sample collection for oil and gas microbial exploration is that all samples are completed at the same time, so as to minimize the impact of samples due to environmental changes; although, this effect is fairly weak, but simultaneous sampling is impossible, and the best way is to speed up the sampling. The sample collection time for oil and gas microbial exploration should avoid the planting season as much as possible to reduce the influence of factors such as fertilization, irrigation, and pesticides. For field sample collection, generally choose winter or early spring (except permafrost) for the favorable results. The depth of sample collection for oil and gas microbial exploration is generally below the root system of the surface vegetation and above the surface water diving surface. Methane-oxidizing bacteria and light hydrocarbon-oxidizing bacteria are aerobic microorganisms, which are easily disturbed by surface organisms if they are too shallow, and are easily affected by groundwater if they are too deep. Sampling at uniform depth is to ensure comparability. The selected area has flat terrain, convenient transportation, and stable climate, which is conducive to the natural storage of samples. Through reasonable organization, increasing the collection team, and increasing the working time as much as possible, the field collection efficiency is greatly improved, and the reliability of the later laboratory analysis work is also guaranteed during sample collection cycle.

3.2. Research on Microbial Abnormality Index System. The Geology and Microbiology Laboratory of Yangtze University has established a set of index systems based on its own experience and has established a set of index systems in Songzi

Table 2: Summary of MPOG data of Xifeng Oilfield in Changqing.

No.	X	Y	MOB	HOB	No.	X	Y	MOB	HOB
1	18728081	3946283	20.60	22.80	30	18741880	3950736	31.40	59.80
2	18728557	3946436	23.60	34.50	31	18742356	3950889	47.10	58.90
3	18729033	3946590	29.70	76.20	32	18742832	3951043	93.40	129.20
4	18729509	3946743	81.70	80.10	33	18735614	3942285	33.10	43.00
5	18729984	3946897	94.60	97.50	34	18735560	3942782	20.70	32.00
6	18730460	3947050	29.00	32.80	35	18735506	3943279	60.70	83.00
7	18730936	3947204	26.70	31.50	36	18735452	3943776	25.60	52.70
8	18731412	3947357	23.30	44.00	37	18735399	3944273	23.30	52.40
9	18731888	3947511	58.70	64.90	38	18735345	3944770	28.00	35.00
10	18732363	3947665	24.80	77.60	39	18735291	3945267	39.30	50.60
11	18732839	3947818	52.60	60.90	40	18735237	3945765	26.60	56.10
12	18733315	3947972	51.60	32.00	41	18735183	3946262	53.90	60.60
13	18733791	3948125	43.20	54.60	42	18735129	3946759	58.20	42.00
14	18734267	3948279	36.60	45.70	43	18735075	3947256	20.50	22.50
15	18734743	3948432	21.50	42.00	44	18735022	3947753	31.70	71.80
16	18735218	3948586	29.60	52.90	45	18734968	3948250	20.50	50.30
17	18735694	3948739	40.40	42.30	46	18734914	3948747	68.60	66.90
18	18736170	3948893	28.30	39.20	47	18734860	3949244	79.60	82.80
19	18736646	3949047	44.60	70.60	48	18734752	3949741	29.30	55.30
20	18737122	3949200	55.40	116.40	49	18734752	3950238	38.10	89.50
21	18737598	3949354	61.00	52.00	50	18734698	3950735	55.70	76.10
22	18738073	3949507	24.30	73.40	51	18734644	3951233	52.20	106.80
23	18738549	3949661	36.80	74.30	52	18734591	3951730	24.10	53.90
24	18739025	3949814	52.50	53.80	53	18731009	3953898	37.10	33.50
25	18739501	3949968	31.00	23.90	54	18730858	3953884	75.00	86.00
26	18739977	3950121	80.70	95.30	55	18733230	3953067	56.30	66.30
27	18740453	3950275	33.00	62.80	56	18733128	3952926	45.00	59.00
28	18740928	3950428	23.10	45.00	57	18733213	3952675	37.40	63.30
29	18741404	3950582	40.70	71.70					

Unit: MU; MOB: methane oxidizing bacteria; HOB: hydrocarbon oxidizing bacteria.

Oilfield in Jianghan Basin, Xifeng Oilfield in Ordos and Changqingqiao Block, Huhe Area in Hetao Basin, Daqing Satellite Oilfield in Songliao Basin, and Binbei Oilfield in Songliao Basin. It has been successfully applied in areas such as the west end of the Gangxi structure in the Bohai Bay Rim Basin and the Yangxin area. The main principle is that according to the characteristics of the work area, combined with the previous practical experience, a set of microbial abnormality index system is established accordingly.

To evaluate microbial abnormalities, we adopted a set of evaluation criteria for hydrocarbon oxidizing bacteria (including methanotrophs) in soil value MU (Measurement Unit), namely, the number of microorganisms (n), activity (a), microscopic identification results (o), formation pressure (f), surface temperature (t), sample moisture (h), lithology (l), color in a comprehensive unit soil sample (c), pH value (p) and surface vegetation (v), and other factors, obtained through a series of treatments.

$$\mathrm{MU} = f(n, a, o, f, t, h, l, c, p, v). \tag{1}$$

The MU index system is used to comprehensively evaluate the cell number of microorganisms and their influencing factors, as shown in Table 1. It converts tedious microbial experimental results of different orders of magnitude into measurement units that are easy to understand and operate for geologists through mathematical model processing and facilitates comparison under the same geological background and ecological conditions to determine background values and outliers. The MU value has no unit and is not an absolute value. It depends on factors such as the ecological conditions of the surveyed area. The MU value consists of nearly ten groups of raw data. These raw data come from microbial microscopic measurement data, biochemical reaction measurement data, growth activity measurement data, CO_2 generation rate data, sensitivity analysis results, light hydrocarbon gas consumption analysis, etc. Using this method, MU value of each measurement point is calculated and recorded on the oil distribution plan and gas distribution plan, respectively, and the MU contour can be obtained. Then, the oil field will be more likely found.

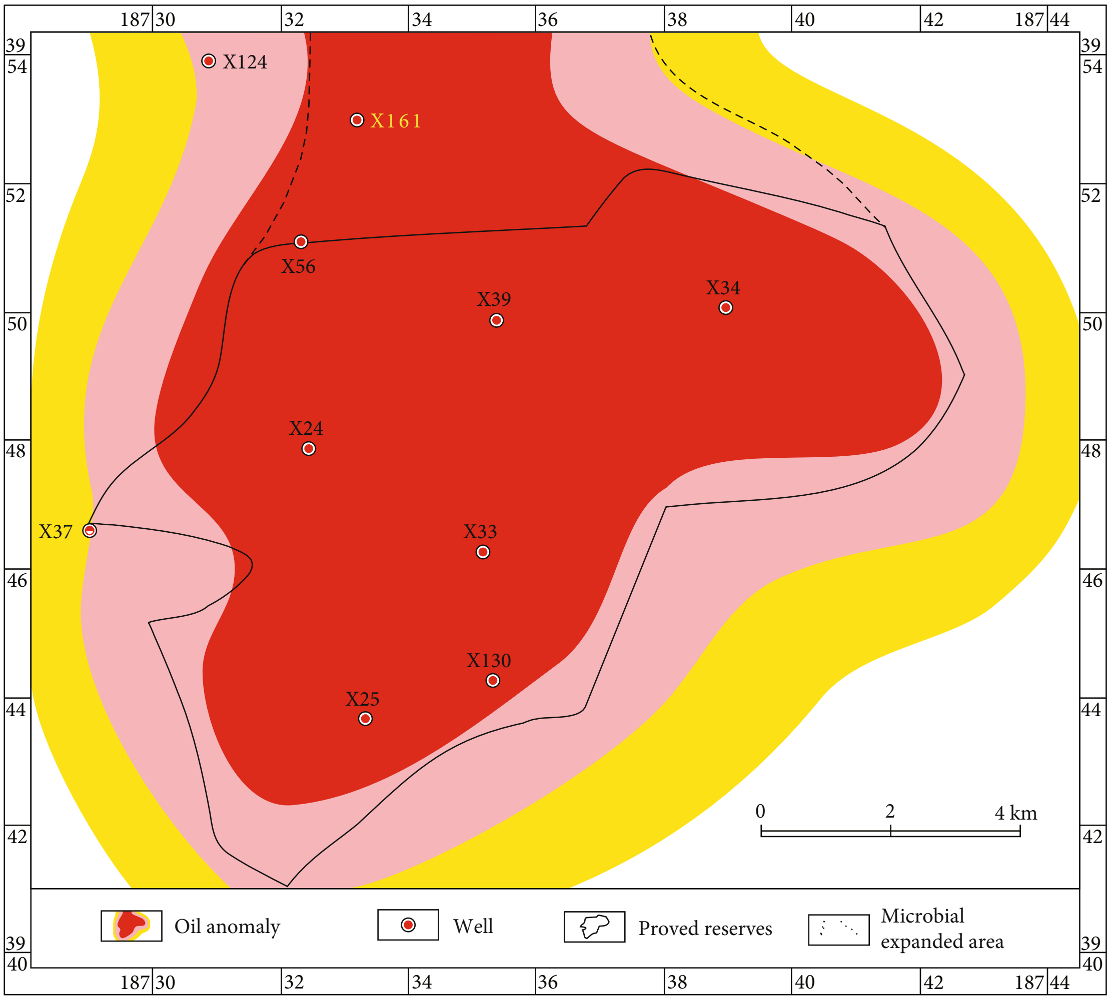

FIGURE 4: Anomalous characteristics of reservoir microorganisms in Dongzhiyuan block, Xifeng Oilfield, Changqing.

4. Principles and Methods of Microbial Exploration Technology

The Ordos Basin is rich in resources, with a distribution pattern of "full basin of gas and half-basin oil" on the plane and "oil on top and gas on the bottom" vertically. As seismic exploration technology is limited in the region, a pilot test study of microbial exploration technology was carried out in Dongzhiyuan block of Xifeng Oilfield in Changing. The work area covers an area of 10 square kilometers and has an average permeability of 1.1 millidarcy, belonging to an ultralow permeability reservoir. The contiguous characteristics of the abnormal area in this work area are similar to the abnormal characteristics of the western end of the Gangxi structure, that is, the area of the abnormally high value area and the low value area of the reservoir microorganism are not much different. However, the reservoirs in this area are obviously different from the former two. In this work area, from bottom to top, it has roughly experienced changes from fluvial facies-delta facies-lake facies-delta facies, showing that there are many multilayer systems in the vertical direction. Therefore, reservoir microbial anomalies show the distribution characteristics of contiguous distribution on the plane (Figure 3 and Table 2).

Based on the data in Table 2 and the geological characteristics of Xifeng Oilfield, the variation range of the abnormal value of microbial oil in Changqing Oilfield is 22.50 (measurement point 43) to 129.20 (measurement point 32), the overall average value is 59.82. The variation range of the abnormal value of microbial gas is 20.50 (measurement point 43) to 94.60 (measurement point 5), and the overall average value is 42.32 (Figure 4).

The average value of the whole area is as follows: it is predicted that the oil layer will be drilled. The drilling results show that the initial test production of well X161 is 12.75 t/d after the completion of drilling, which is consistent with microbial results, and prediction of the expansion of the reservoir boundary to the north has also been confirmed.

5. Conclusions

(1) The oil anomaly in the whole work area is very strong, forming a contiguous distribution, which shows that the oil and gas prospect is favorable

(2) According to the display area of microbial anomaly, it is not only basically consistent with the proved area but also the oil area should expand to the north. It has been confirmed by the well X161 drilling

(3) This research has important reference significance for predicting the distribution of remaining oil and gas, rapid predrilling evaluation of a single well, and well-location deployment

Data Availability

Data will be available on request.

Ethical Approval

On behalf of all the co-authors, the corresponding author states that there are no ethical statements contained in the manuscripts.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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