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Distribution of Biogenic Gas Reservoirs and Optimization of Favorable Zones in the Sanhu Area, Qaidam Basin, China

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Abstract: Based on the drilling results of the Taishen-1 well in the Sanhu area in the Qaidam Basin, the study proposed new findings on the conditions of source rock, reservoir, and overlaying strata, as well as accumulation characteristics for biogenic gas. Further, the controlling factors of biogenic gas accumulation as well as two favorable zones for exploration were identified based on the comparison of drilling results and geological findings in adjacent areas. The result of the study showed that: (1) the biogenic gas source rock in the Sanhu area is lacustrine dark mudstone, and the LLTOC (lower limit of total organic carbon) in Q_{1+2} (the Qigequan Formation) and N (the Neogene) is 0.25% and 0.40%; (2) the 'self-generation and self-storage' source-reservoir combination developed across all the formations due to the absence of faults and the development of mudstone; (3) the controlling factors of gas accumulation in the studied area include the limit of burial depth, the methane yield, and climate conditions. The failure of the Taishen-1 well owes to the fact that the gas generated failed to support the demand for gas accumulation; (4) influenced by the southward movement of gas-containing groundwater from the high potential area in the north, the biogenic gas reservoirs are distributed in the northern slope and the central sag of the Sanhu depression, and the lower limit of exploration depth of the biogenic gas reservoirs is about 2119 m; (5) two favorable zones were selected for natural gas exploration: the Upper Tertiary thermogenic gas-bearing Yahu-Sebei area and the biogenic gas-bearing Tainan-Sebei area.

Keywords: biogenic gas; Qaidam Basin; Sanhu area; failure reasons; favorable zones

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1. Introduction

In recent years, major breakthroughs have been made in global biogas exploration, with biogas discoveries of 15 Tcf and 65 Tcf in the Bay of Bengal Rim region and the Eastern Mediterranean, and recoverable reserves in the Leviathan gas reservoir and Zohr gas reservoir in the Eastern Mediterranean deepwaters and ultra-deepwaters amounting to 21.40 Tcf and 22.17 Tcf [1]. Abundant biogas fields are widely distributed in Italy, Colombia, Canada, the Gulf of Mexico, the United States, Russia, etc. [2]. The world's most famous biogas reservoirs include the Gulf of Mexico, Alaska's Cook Bay, the West Siberian Basin, the Carpathian frontier in Poland, the Apennines frontier in Italy, and the Qaidam Basin in China [3], with a total recoverable reserve of 1716 Tcf [4]. Biogenic gas reserves account for 20–30% of the world's natural gas reserves [5,6], making biogenic gas exploration one of the hotspots of natural gas exploration [2,7,8]. The study of biogenic gas was among the focuses of the 2002 AAPG (American Association of Petroleum Geologists) annual meeting, including the formation and distribution, resource potential, and identification methods of biogenic gas and thermogenic gas [2]. Generally, global biogas reservoirs are mainly distributed in new strata with shallow burial depths, featuring low ground surface temperatures and a low underground temperature gradient. The layer of source rocks is mainly humus organic matter with TOC >0.5% [4,5]. The Sanhu depression of Qaidam Basin in China is one of the world-famous biogenic gas distribution areas [9], with its unique accumulation characteristics and distribution rules. The Quaternary "self-generation and self-storage" combination biogenic gas reservoirs are mainly developed, the buried depth is between 80 and 1815 m, and the proven biogenic gas reserves are up to 3000×10^8 m^3 [10–12].

After years of exploration and development, large-scale biogenic gas fields, including Sebei-1, Sebei-2, and Tainan, were discovered consecutively in the Sanhu area, energizing the largest biogenic gas production base in China [13,14]. Several wells in the area, such as Tainanzhong-1, Yishen-1, and Tainan-9, obtained industrial gas flow (Figure 1). In 2010, in order to identify the hydrocarbon potential, gas-bearing, and reservoir properties of N_2^3 (the Upper Tertiary Shizigou Formation) in the Tainan structure, expand biogenic gas exploration in the Sanhu area, and increase the geological reserves of natural gas, the Taishen-1 well was drilled to explore deep gas reservoirs [15]. The drilling results were worse than expected, and the reservoir-forming conditions were quite different from the findings of previous studies. With modern petroleum theory and upgraded technical methods, the authors made an in-depth analysis and re-understanding of the key reservoir-forming conditions in the study area based on the relevant geological data of the Taishen-1 well and its surrounding areas. As a conclusion, the main reasons for the failure of the Taishen-1 well are ascertained, and favorable zones for further oil and gas exploration are proposed, which provides a scientific basis for the subsequent exploration and development of biogenic gas reservoirs in the study area.

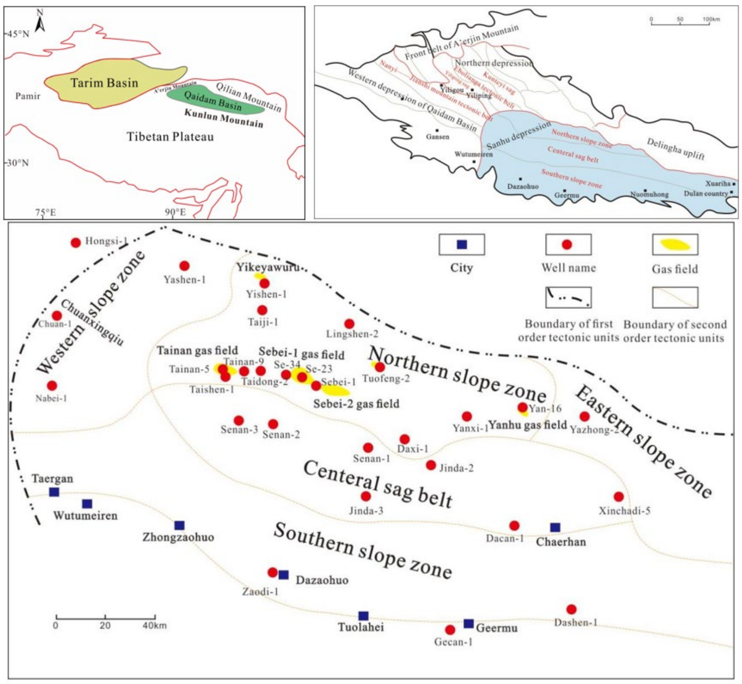

Figure 1. Division of structural units in the Qaidam Basin.

2. Geological Setting

Qaidam Basin is a cut-off basin surrounded by mountain ranges, including Kunlun Mountains, Altun Mountains, and Qilian Mountains, located in the Northwestern Qinghai Province (90°16′ E–99°16′ E, 35°00′ N–39°20′ N). The basin extends about 800 km east-west and 300 km north-south (total area: 240,000 km^2). Previous studies indicated that the Qaidam Basin mainly develops three sets of petroliferous systems, distributing in the northwestern Basin, the Mangya area, and the Sanhu area [16–20]. The petroliferous system in the Sanhu area is characterized by the development of Quaternary biogenic gas reservoirs with three major geological features: weak diagenesis, thinly interbedded sandstone-mudstone, and widespread biogenic gas-bearing strata. The Sanhu (meaning three lakes) area covers about 30,000 km^2, named for the three large salt lakes within. It stretches from the Chuanxingqiu structure in the west to Hubuxun Lake in the east and the Kunlun Mountains in the north [21,22] (Figure 1). The depocenter of the Qaidam Basin shifted from the Tertiary in the west to the Quaternary in the east [23,24]. The Pleistocene–Holocene strata were deposited in the Qaidam Basin during the neotectonic movement since the late Pliocene. It experienced unprecedented high-rate lacustrine sedimentation in the Pleistocene, with the maximum sediment thickness exceeding 2700 m, leaving a stable set of continuous lacustrine sediments [25–27].

The Tainan structure is a buried structure in the Sanhu area, where Quaternary biogenic gas reservoirs are widely distributed. The southern slope zone, the central sag belt, and the northern slope zone extend from south to north (Figure 1). The exploration results confirmed the good potential of source rocks in the Sanhu area. The reservoir is controlled by wide-spread lacustrine beach-bar sandbodies, displaying argillaceous siltstone, siltstone, and a few fine sandstones (Figure 2). It is characterized by loose structure, weak diagenesis, dominating primary pores, a thin single reservoir layer, multiple layers, and good physical properties [28,29]. The main source rocks in the study area are dark lacustrine mudstones of Q_{1+2} and N_2^3 (Figure 2), with large and evenly-spread thickness [30,31]. The kerogen types are $II_{2,}$ and III in the immature stage. A high sedimentation rate leads to relatively scattered and low organic matter. However, the huge sedimentation thickness can effectively compensate for the weakness of source rock maturity in this area [32]. The TOC (Total organic carbon content) in N_2^3 is 0.10~0.80%, with an average of 0.45%, and that in Q_{1+2} is 0.10~0.70%, with an average of 0.40%. Q_{1+2} in the Tainan area has good reservoir properties, with a porosity of 25~35% and a permeability of 10~100 mD. The average reservoir porosity of N_2^3 is 18.8~24.5%. The caprock is mainly mudstone covering the upper part of N_2^3 and Q_{1+2}, which has a rather high porosity and low specific surface area with a certain sealing ability. Two types of biogenic gas reservoirs were discovered. The first type is the anticlinal traps, including Tainan, Sebei, Yikeyawuru, Taijinaier, Yanhu, and Tuofengshan traps. These anticlines were formed in the late sedimentary stage of N_2^3 and the early Quaternary stage. The second type is stratigraphic traps developed in a tectonic setting, mainly distributed in nose-like structures or slopes such as Taidong, Sedong, Tuoxi, Yanxi, etc. They are mainly distributed on the north slope, which can be divided into three types: sandstone lens, updip sandstone pinch-out, and lateral variation.

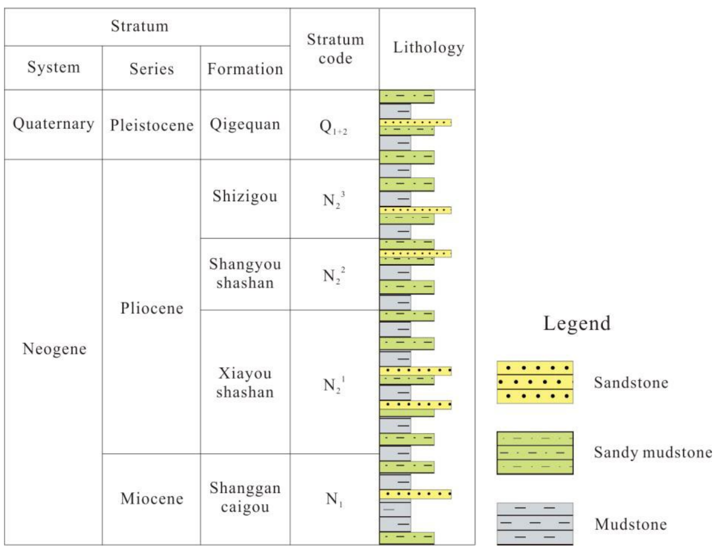

Figure 2. Comprehensive histogram of the study area.

3. Petroleum Geological Conditions

Several biogenic gas fields were discovered in the Qaidam Basin, such as Sebei-1, Sebei-2, Tainan, Yikeyawuru, Yanhu, etc. [33]. The study area is endowed with good reservoir-forming conditions, as the highest daily gas production of N_2^3 (1098~1319 m) in the Yishen-1 well reached 100,000 m^3, and the Beican-3 well produced gas continuously for 40 years. In order to identify the gas content of N_2^3 in the deep and sag belt of the Sanhu area and expand the exploration area for biogas, the Taishen-1 well was deployed in the Tainan-Sebei uplift zone between the Taijinaier Lake and Senie Lake depressions (Figure 1), on the northern slope of the Sanhu depression. The drilling results revealed that a gas-measuring abnormal section developed in Q_{1+2} and N_2^2, and the total hydrocarbon curve of gas logging reflects the real-time hydrocarbon gas content in the drilling fluid, indicating that Q_{1+2} and N_2^2 contain hydrocarbon gas (Figure 3a). However, the modular formation dynamics tester result indicated that the two strata were both water-bearing and low-water-producing layers (Figure 3a). The gas measurement of N_2^3 showed no abnormity, implying the failure of the Taishen-1 well. From top to bottom, the Taishen-1 well encountered Q_{1+2}, N_2^3, and N_2^2 (the Shangyoushashan formation) in sequence (Figure 2). Based on the analysis of source rock conditions, reservoir and overlaying strata of the target strata of the Taishen-1 well, combined with the comparison of petroleum geological setting and dynamical condition for the underground water in adjacent areas, the authors made a deep analysis and re-understanding of the petroleum geological conditions, identified the distribution rules of biogenic gas reservoir in the study area, and proposed the favorable gas exploration zones in the study area as well as the direction for further gas exploration.

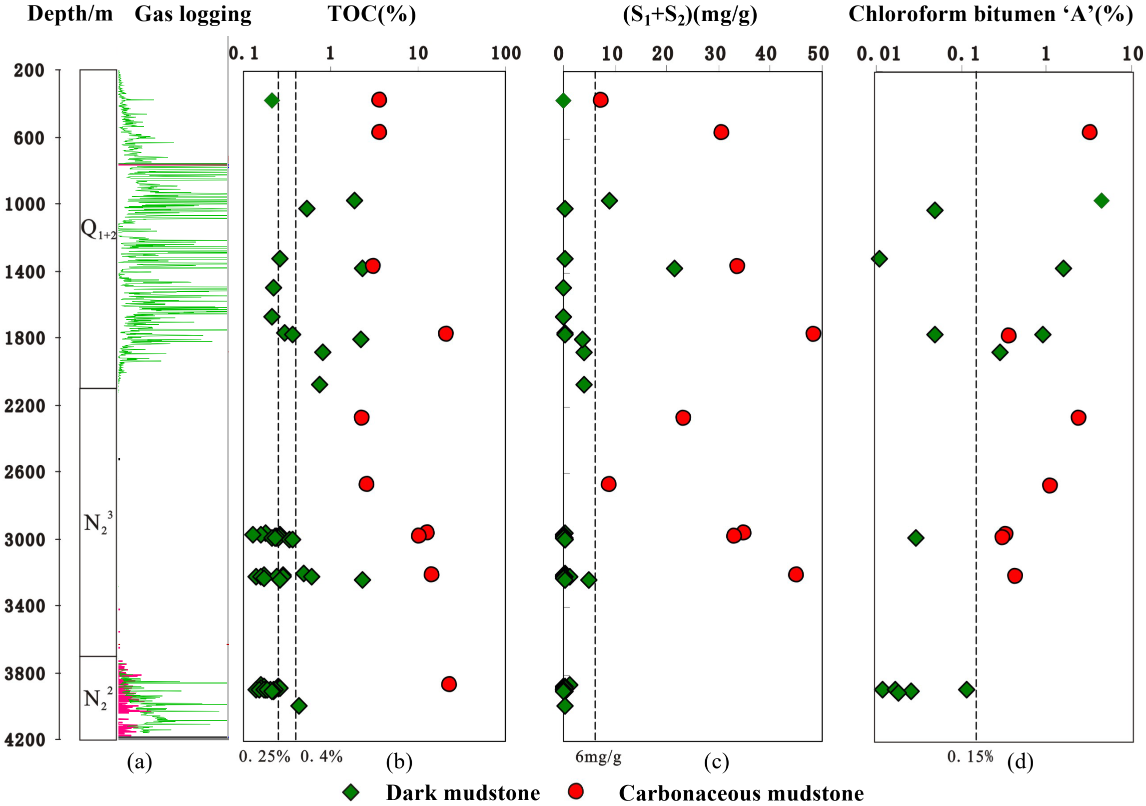

Figure 3. Gas logging anomaly and organic matter abundance evolution profile of the Taishen-1 well.

3.1. Source Rocks

Previous studies [34,35] suggested that the lower limit of TOC of the Quaternary biogenic gas source rocks in the study area is 0.25% and that of the Upper Tertiary biogenic gas source rocks is 0.4%. Through the analysis of drilling core samples, it has been found that the average TOC in the Quaternary gas source rocks is 0.32%, the average content of chloroform asphalt 'A' is 100 mg/L, the average content of total hydrocarbons is 292 mg/L, and the organic matter type is mainly humic and partial humic mixed type. The Ro (vitrinite reflectivity) ranges between 0.25% and 0.45% in the immature stage [36]. However, Tainan, Sebei-1, and Sebei-2 gas fields showed relatively large gas reserves and production capacities.

3.1.1. Evaluation of Source Rocks

Three sets of source rocks were encountered in the Taishen-1 well, which were $N_2{}^2$, $N_2{}^3$, and Q_{1+2} from bottom to top (Figure 2), with dark mudstone and carbonaceous mudstone developing. The thick, dark lacustrine mudstone serves as the main source rock in the study area [37]. The abundance of organic matter was determined with the methods of TOC, $S_1 + S_2$ (hydrocarbon potential), and chloroform asphalt 'A'. TOC refers to the percentage of carbon contained in all organic matter in the rock relative to the total weight of the rock, which is a common indicator for evaluating the abundance of organic matter. $S_1 + S_2$ refer to the residual and potential oil and gas production of source rock, which can accurately reflect the total amount of oil and gas that can be generated, which is a common index for evaluating the abundance of organic matter. The chloroform asphalt 'A' refers to soluble organic matter extracted directly from rocks with chloroform, which is a good indicator for evaluating the abundance of organic matter. According to the composition analysis of Kerogen [38], the types of kerogens were clarified in the VanKrevelen diagram. The characteristics of each set of source rocks are as follows:

$N_2{}^2$ is located from 3730 to 4291 m in depth, with an apparent thickness of 561 m. The lower boundary of $N_2{}^2$ was not penetrated by the Taishen-1 well. The lithology is mainly gray, brown-gray, light gray, dark gray, sandy mudstone, and argillaceous siltstone. The TOC ranges from 0.14% to 0.34% with an average of 0.21% (Figure 3b), and the $S_1 + S_2$ range from 0 to 1.25 mg/g with an average of 0.18 mg/g (Figure 3c). The chloroform asphalt 'A' ranges from 0% to 0.113%, with an average of 0.011% (Figure 3d). The organic matter is mainly Type III and a few Type II_2 (Figure 4), which belong to poor-grade source rocks.

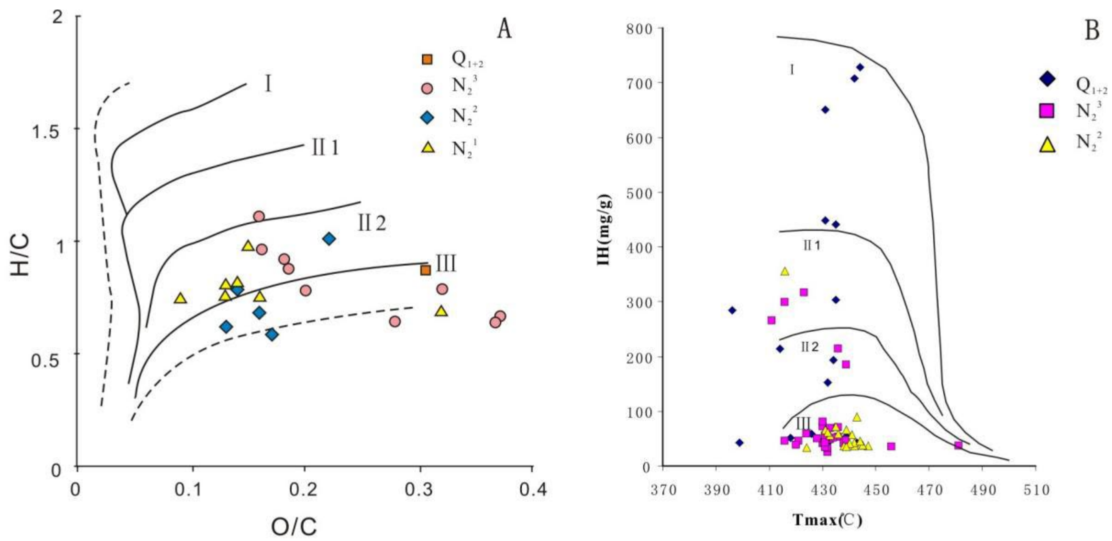

Figure 4. Classification of organic matter by elemental analysis. (**A**) Relation between O/C and H/C of kerogen. (**B**) Relation between hydrogen index of kerogen and pyrolysis Tmax.

$N_2{}^3$ is located from 2108 to 3730 m in depth, with an apparent thickness of 1622 m. The lithology is mainly gray, brown-gray, light gray, dark gray, sandy mudstone, and argillaceous siltstone. The TOC is 0.13~2.33% with an average of 0.34% (Figure 3b). The $S_1 + S_2$ are 0.08~5.02 mg/g, with an average of 0.37 mg/g (Figure 3c). The chloroform asphalt "A" is 0~0.03% with an average of 0.003% (Figure 3d). The main types of organic matter are II_2 and III, with a few II_1 (Figure 4), which belongs to the middle-grade source rocks.

Q_{1+2} is located from 0 to 2108 m, with an apparent thickness of 2108 m. The lithology is mainly gray, light gray, dark gray, and sandy mudstone. The TOC ranges from 0.21% to 2.32%, with an average of 0.9% (Figure 3b). The $S_1 + S_2$ range from 0.12 to 21.4 mg/g, with an average of 3.89 mg/g (Figure 3c). The chloroform asphalt "A" ranges from 0% to 4.367%, with an average of 0.658% (Figure 3d). Type I, type II_1, type II_2, and type III kerogens coexist (Figure 4), which have certain hydrocarbon-generating abilities and belong to middle-grade source rocks.

The results of sample analysis in the Taishen-1 well proved that the source rock entered the low mature stage at 2800 m (during 1.78 Ma), with a corresponding Ro value of 0.5%, and entered the mature stage at 4000 m (during 0.34 Ma), with a corresponding Ro value of 0.8% (Figure 5). In general, the Taishen-1 well encountered strata with low organic abundance. The order from high to low of the organic abundance of source rocks is Q_{1+2}, $N_2{}^3$, and $N_2{}^2$. The organic matter in the source rocks is mainly from higher plants and partly from aquatic organisms. The organic matter types are mainly II_2 and III, which are beneficial to the formation of natural gas (Figure 4).

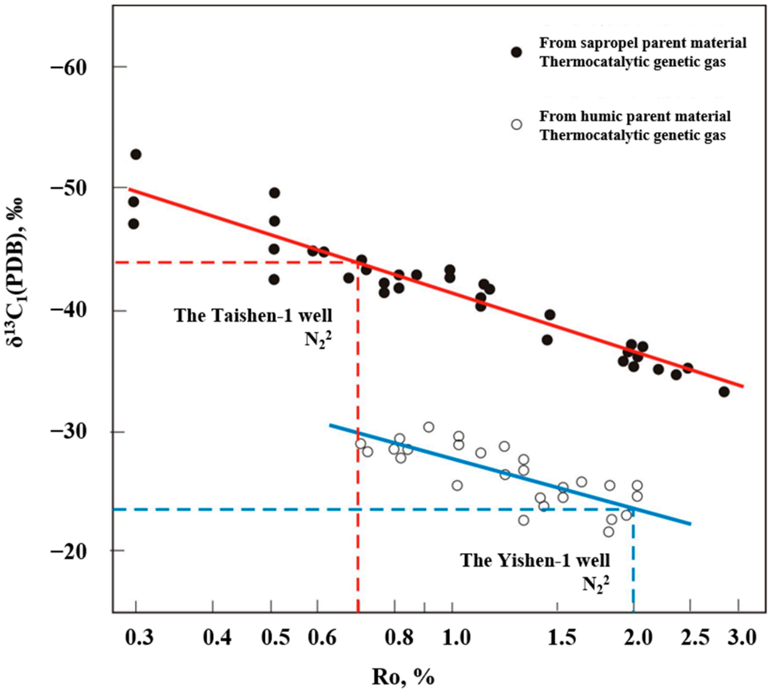

Figure 5. The relationship between the $\delta^{13}C_1$ of $N_2{}^2$ natural gas and Ro of its parent rock encountered by the Taishen-1 and Yishen-1 wells.

3.1.2. Gas-Source Correlation

Based on the results of carbon isotope analysis and petroleum geological analysis, it is confirmed that the natural gas of $N_2{}^2$ and Q_{1+2} are both from "self-generated and self-storage" combinations. The carbon isotopic composition of biogenic gas, oil-type gas, and coal-type gas differs greatly from each other. Therefore, carbon isotopes ($\delta^{13}C_1$) are widely used in oil and gas-source correlation [32–35]. In general, ① the carbon isotope values of biogenic gas are the lowest: $\delta^{13}C_1 \leq -65‰$, $\delta^{13}C_2 \leq -46.52‰$, $\delta^{13}C_3 \leq -32.58‰$. ② The carbon isotope composition of oil-type gas is higher than that of biogenic gas, but lower than that of coal-type gas, with $\delta^{13}C_1$ ranging between −30~−55‰, $\delta^{13}C_2$ −28.8~−37‰, and $\delta^{13}C_3$ −25.5~−32‰. ③ The carbon isotope composition of coal-type gas is the highest: $\delta^{13}C_1$ ranges from −10‰ to −43‰, $\delta^{13}C_2$ is above −25.1‰, $\delta^{13}C_3$ is above −23.2‰.

Table 1 suggested that the $\delta^{13}C_1$ of $N_2{}^2$ encountered by the Taishen-1 well is between −35.5‰ and −47.3‰, with an average of −43.6‰, indicating a thermogenic gas origin. It is lower than the value of $\delta^{13}C_1$ from the Jurassic gas (−18.3~−22.5‰). The results indicated that the N_2^2 gas encountered by the Taishen-1 well is not biogenic gas or coal-derived gas from the Jurassic but self-generating oil-type gas. Based on the relationship between Ro and $\delta^{13}C_1$ of natural gas established by Stahl, the calculated maturity of natural gas is 0.7% (Figure 5), which is consistent with the measured maturity of total organic matter in source rocks of N_2^2. The results confirmed that the N_2^2 gas encountered by the Taishen-1 well is formed by the source rock of N_2^2. In addition, the gas logging anomaly section of N_2^2 in the Taishen-1 well is rich in total organic matter content, which corresponds well to the gas logging anomaly section. In addition, because the N_2^2 reservoir is of poor property and lacks a migration pathway, it is difficult for gas from the surrounding and underlying formations to migrate to the N_2^2 reservoir.

Table 1. Carbon isotope analysis of the Tertiary natural gas in the Taishen-1 well.

Sample No.	Sample Depth/m	$\Delta^{13}C_1$/‰	$\delta^{13}C_2$/‰	$\delta^{13}C_{co2}$/‰
16	4084.0~4090.0	−40.2		−18.3
18	4104.0~4105.0	−47.3	−29.7	−19.0
21	4131.0~4135.0	−45.7	−28.9	−19.2
23	4189.0~4190.0	−46.9	−30.1	−17.8
25	4206.0~4208.0	−46.1	−29.7	−17.7
26	4211.5~4212.0	−35.5	−25.2	−19.3

The characteristics of the gas logging abnormal section of Q_{1+2} indicated a high TOC and poor reservoir physical properties. In addition, the underlying layer has no hydrocarbon-generating ability and lacks a gas migration pathway, preventing the natural gas from surrounding and lower formations from migrating here. It is thus inferred that the natural gas in Q_{1+2} is also from the "self-generation and self-storage" combination.

3.2. Reservoirs

N_2^2 and N_2^3 from the Taishen-1 well are mainly shore-shallow lacustrine facies, whereas Q_{1+2} is mainly shallow lacustrine facies. The different depositional environments of each formation resulted in different reservoir characteristics. Through the experimental analysis of core samples from the Taishen-1 well, the reservoirs of each formation are systematically evaluated. The lithology data show that the reservoir lithology of the Taishen-1 well is mainly argillaceous siltstone, siltstone, and fine sandstone, with a cumulative thickness of 1828.97 m and a reservoir-strata ratio of 42.6%.

The reservoir of N_2^2 is mainly composed of gray argillaceous siltstone and siltstone of shore lacustrine facies. The thickness is 204 m, accounting for 36.4% of N_2^2. There are two siltstone reservoirs, which have 10 layers and a cumulative thickness of 24 m. Since the formation revealed by the Taishen-1 well is nearly 560.9 m in the upper part, the lithology in the deeper lower part should be relatively coarse-grained. The porosity ranges from 2.1% to 11.8% with an average of 10.75%, and the permeability ranges from 0.0001 to 0.01 mD with an average permeability of 0.007 mD, belonging to the low porosity-low permeability reservoir. Poor pore structure and a micro-fine pore throat are unfavorable to hydrocarbon accumulation (Figure 6).

The reservoir of the N_2^3 formation is gray fine sandstone and argillaceous siltstone deposited in shore-shallow lacustrine. The silty mudstone and mudstone are interbedded, and the reservoirs are relatively well developed. The cumulative thickness of sandstone is 72.25 m, and the maximum thickness of a single layer is 16 m. The porosity is mainly in the range of 6.8~24.85%, with an average of 15.8%. The permeability is mainly in the range of 0.047~1000 mD with an average of 12.02 mD, which belongs to the medium-high porosity–medium-low permeability reservoir. The casting thin sections showed that the intergranular pores of N_2^3 were well developed, and feldspar dissolution and secondary pores were commonly observed, indicating good pore connectivity.

The reservoir of Q_{1+2} is mainly gray argillaceous siltstone of shallow lacustrine facies. The accumulative thickness of the reservoir is 1024 m, and the reservoir-strata ratio is 48.7%.

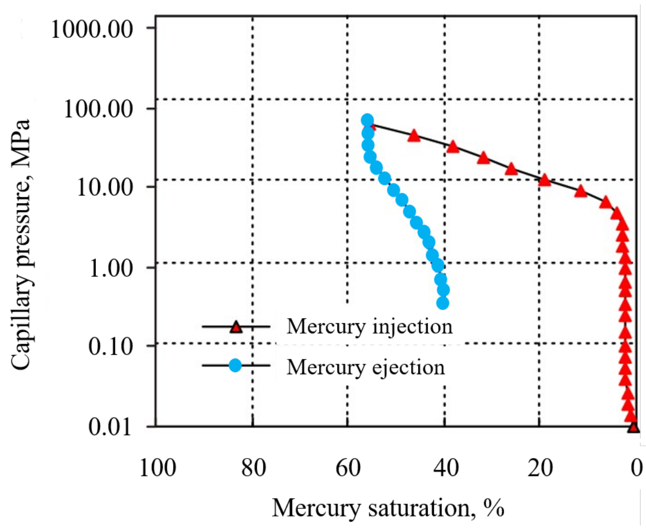

Figure 6. Capillary pressure curve of the Tertiary gray siltstone in the Taishen-1 well. (Depth: 3896.5 m, $N_2{}^2$).

The porosity and acoustic curves varied with depth, which showed that as the burial depth increased, the physical properties such as porosity and permeability decreased significantly (Figure 7). In addition, there are high-porosity dissolution zones in $N_2{}^3$ at about 3200 m. On the whole, $N_2{}^3$ occupies the best porosity among others.

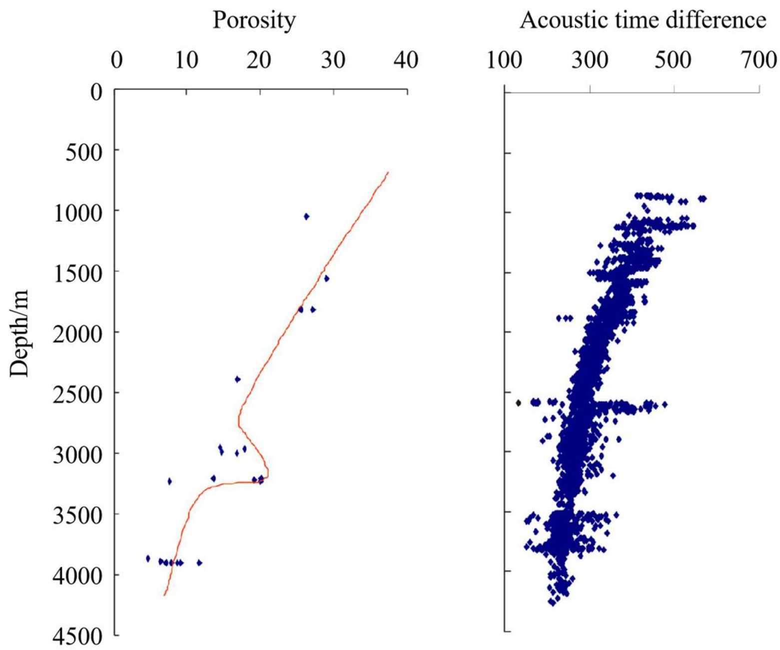

Figure 7. The relationship between porosity and acoustic time difference with depth.

3.3. Caprocks

The mudstone caprock of the Quaternary biogenic gas reservoir in the Qaidam Basin is in the early diagenetic stage and has the characteristics of high porosity and permeability [39–41]. The whole biogenic gas reservoir is in a weak sealing state, but the existence of large-scale gas fields confirms a unique sealing mechanism and model. It is considered that the sealing-seepage of gas reservoirs is a dynamic equilibrium process, and the superimposed reservoir and caprock cover a certain amount of gas by displacement pressure difference [41]. In addition, the formation was saturated with formation water with high salinity, and the retained water filled the pores of mudstone, which reduced the permeability of caprocks. The caprock is also the source rock, which can form a hydrocarbon concentration seal and prevent the vertical migration of natural gas. The thickness of caprock plays a very important role in compensating for its sealing ability [40,41]. The thickness of mudstone in Q_{1+2} encountered by the Taishen-1 well is up to 1076 m, but it is characterized by shallow burial depth, high water content, good physical properties, and low maturity of total organic matter due to its early diagenetic stage. It provided the necessary living environment for methanogenic bacteria to breed but also reduced the efficiency of biogenic gas accumulation, which requires a large amount of biogenic gas to form commercial natural gas accumulation [42–47]. This may also be an important reason why the Taishen-1 well failed to identify biogenic gas reservoirs in Q_{1+2}. Similar to Q_{1+2}, the well-developed N_2^3 and N_2^2 mudstones were buried deep and strongly compacted, which effectively improved the sealing ability of mudstones. Generally speaking, the three sets of formations encountered by the Taishen-1 well have a certain sealing ability, which was gradually enhanced from shallow to deep.

The dark mudstone is the main gas source rock in the study area, which has been in a continuous biochemical gas production stage since the deposition of N_2^3. The gas accumulates in the adjacent sandstone reservoir through the vertical migration of gas nearby or the lateral migration over a short distance, forming the natural gas reservoir with "self-generation and self-storage".

4. Main Controlling Factors

4.1. Depth Limit

Biogenic gas has a strict requirement for temperature, which must be lower than 65 °C in the Qaidam Basin, with the best range being 35~55 °C [48,49]. The lower limit of biogenic gas formation is generally defined as 80 °C [50–52]. The current gradient temperature is 3.6 °C/100 m, and the average surface temperature is 3.7 °C in the Qaidam Basin. Based on the lower limit of biogenic gas at 80 °C, the optimal depth of biomethane formation is between 900 and 1600 m, and the lower limit of biogenic methane formation depth is about 2119 m. The burial depth of N_2^3 in the Taishen-1 well is between 2108 and 3730 m, which is greater than the lower limit of the depth of biogenic gas and is unfavorable for biogenic gas production. The gas reservoir of N_2^3 is buried between 1098 and 1319 m in the Yishen-1 well, which is above the lower limit of biogenic methane depth.

4.2. Methane Production Rate

The results of the simulated biogenic gas production experiment (Figure 8) of N_2^3 and Q_{1+2} verified that the methane production rate in the upper part (above 400 m) of Q_{1+2} is lower than that in the middle and lower parts (700~1600 m). The methane production rate in the middle-lower part of Q_{1+2} is 3~4 times as high as that of the shallow layer. The methane yield of N_2^3 in the Upper Tertiary is generally low; only one third of the middle and lower parts of the Q_{1+2} formation. The lower limit of TOC of the source rock is higher than the lower limit of TOC generation for biogenic gas reservoirs in the Tertiary because the methane yield of N_2^3 in the Upper Tertiary is lower than that of Q_{1+2} in the Quaternary. Previous studies [26] have shown that the methane production rate of the Tertiary source rocks is low. Therefore, the lower limit of TOC for gas production should be higher than 0.25% when the Tertiary biogenic gas source rocks are evaluated.

By comparing and analyzing the TOC of N_2^3 from the Yishen-1, Lingshen-2, Hongsi-1, and Taishen-1 wells, it is found that the TOC of N_2^3 in the Yishen-1 well is more than 0.4%, the average value is 0.5%, and the industrial gas flow section corresponds well with the section with the high TOC (Figure 9). The TOC of N_2^3 in the Lingshen-2, Hongsi-1, and Taishen-1 wells is 0.4% or less, and no industrial gas flow was obtained (Figure 9). Therefore, it is possible to obtain biogenic gas industrial flow in N_2^3 if the TOC value is greater than 0.4% (Well Yishen-1). The TOC of N_2^3 of the Taishen-1 well is 0.4%, below the lower limit of TOC generation in the Upper Tertiary biogenic gas reservoir.

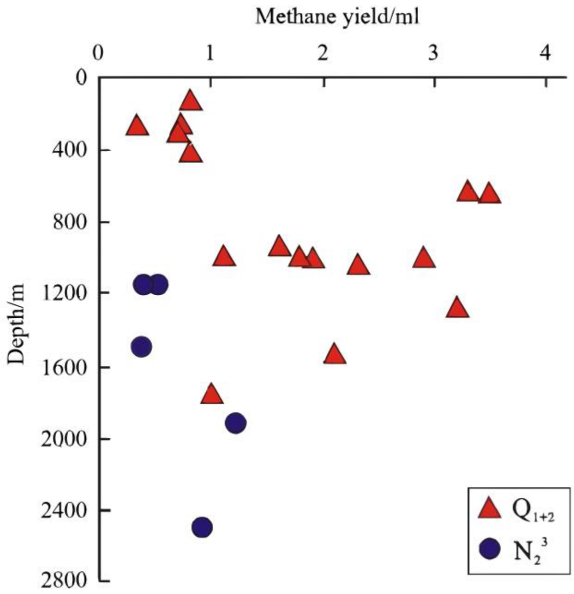

Figure 8. Change in methane yield of Q_{1+2} and $N_2{}^3$.

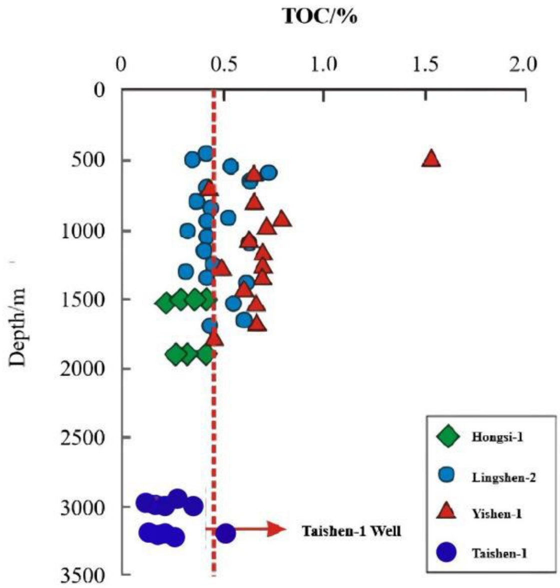

Figure 9. Vertical variation of TOC in the Tertiary source rocks.

4.3. Climate Impact

It is well known that the temperature of the environment greatly influences biochemical processes, which are important for the formation and accumulation of biogenic methane. The experimental results indicated that the survival temperature of methanogens was 0~75 °C, while the optimum metabolic temperature was 30~60 °C [48]. The process of methane production by methanogens is rather slow at a low temperature of 0~15 °C but significantly accelerates when the ambient temperature is higher than 15 °C, and the gas production rate can be correspondingly increased by 10 times. The bacteria investigation found that methanogens existed in the Quaternary mudstones of the Sanhu area in the Qaidam Basin from the modern lake mud to the depth of 1705 m, which suggested a likely biochemical production of methane in the Quaternary since the Tertiary.

Previous research confirmed that the Tertiary climate was warmer, wetter, and more stable than the present [51–55]. The warm climate of the Tertiary period was favorable for source rocks to produce biogenic gas when they were buried shallowly, and the biogenic gas in the shallow layer was then lost because the source rocks could not accumulate into reservoirs, and a considerable amount of organic matter was consumed, which was not conducive to the preservation of organic matter. On the contrary, the Quaternary glaciers were widely distributed, and the global low-temperature climate effectively inhibited the activity of methanogens under superficial conditions and avoided excessive consumption of organic matter in the shallow-buried stage, thus delaying the peak of biogenic gas production. Consequently, quaternary biogenic gas can be generated and accumulated at a large depth.

4.4. Controlling Factors

As mentioned above, the depth limits, methane production, and climate impact are the controlling factors of biogenic gas accumulation in the study area. $N_2{}^3$ from the Taishen-1 well is an authigenic, self-generated, and self-storage genetic gas, and the lower limit of TOC in the Tertiary source rocks is 0.4%. The average TOC of $N_2{}^3$ from the Taishen-1 well is 0.34%, which is below the lower limit of 0.4% for biogenic gas generation and accumulation in the Tertiary. This is the fundamental reason why the Tertiary system from the Taishen-1 well failed to obtain industrial gas flow.

The burial-hydrocarbon generation history of the Taishen-1 well (Figure 5) revealed that the organic matter of $N_2{}^3$ source rock is in the immature-low mature stage and that of $N_2{}^2$ source rock is in the low mature-mature stage. Table 2 showed that the source rocks of $N_2{}^2$ from the Taishen-1 well have low organic matter abundance and are in the late maturation stage. Therefore, the maturity of $N_2{}^2$ source rocks did not reach the stage of producing large amounts of pyrolysis gas and thermal metamorphism gas and failed to produce large amounts of natural gas. $N_2{}^3$ is mainly in the immature-low mature stage with a low gas-generating ability. Therefore, the Taishen-1 well did not encounter the self-generating and self-storage thermal genetic gas reservoir.

Table 2. Geochemical data of sample from the Taishen-1 well.

Formation	Sample Depth/m	TOC/%	Chloroform Bitumen 'A'/%	$S_1 + S_2$/(mg/g)
Q_{1+2}	0~2087	0.21~2.32/0.84(12)	0.0048~4.3658/0.904(7)	0.113~21.44/3.57(12)
$N_2{}^3$	2087~3747	0.13~2.33/0.34(26)	0.0029~0.0298/0.0085(31)	0.08~5.02/0.37(26)
$N_2{}^2$	3747~4350	0.15~0.44/0.21(20)	0.0034~0.1132/0.018(12)	0.072~1.25/0.19(21)

In short, the burial depth of $N_2{}^2$ and $N_2{}^3$ in the Taishen-1 well is greater than the lower limit of the mass production depth of biogenic methane (2119 m), and there are no favorable temperature and climatic conditions for biogenic methane accumulation and preservation in the Upper Tertiary [12]. In addition, the TOC does not reach the lower limit of 0.4% for biogenic methane [30]. Therefore, $N_2{}^2$ and $N_2{}^3$ in the Taishen-1 well have no conditions for biogenic gas accumulation. The reservoir conditions of each formation from the Taishen-1 well are poor, with low permeability and a lack of fault communication. It is difficult for the natural gas from the surrounding and lower strata to enter the trap. Therefore, $N_2{}^2$ thermogenic gas and the biogenic gas from Q_{1+2} are both self-generated and self-storage. $N_2{}^2$ from the Taishen-1 well is endowed with low organic matter abundance. It entered the mature stage at a late time, thus limiting the duration of hydrocarbon generation and maturation and leaving no chance for a large amount of natural gas to be produced. $N_2{}^3$ is mainly in the immature-low mature stage with poor gas generation ability. Therefore, the self-generated and self-storage genetic gas in the Taishen-1 well failed to form a gas reservoir.

5. Favorable Zone Optimization

5.1. Oil and Gas Distribution Characteristics

At present, seven biogenic gas fields have been discovered in the Qaidam Basin, including Sebei-1, Sebei-2, Tainan, Taijinaier, Yikeyawuru, Yanhu, and Tuofengshan. They are mainly distributed in the northern slope belt and the central depression belt, but industrial gas reservoirs have not been found in the southern slope belt up to now [56]. Previous studies [56,57] suggested that the meltwater from the south Kunlun Mountains replenishes groundwater in the central depression of the Sanhu region, carrying dissolved biogenic gas up to the northern slope. Therefore, the biogenic gas is mainly distributed in the structurally high parts of the central sag belt and the northern slope zone. Previous studies have not reached a common understanding of the favorable zones for biogenic gas in the Qaidam Basin [44,57–59]. By analyzing the migration of the hydrocarbon-generating centers of sedimentary basins (Figure 10) and the influence of groundwater flow from the south, we infer that the gas fields are likely located around the hydrocarbon generation sags and the northern slope zone.

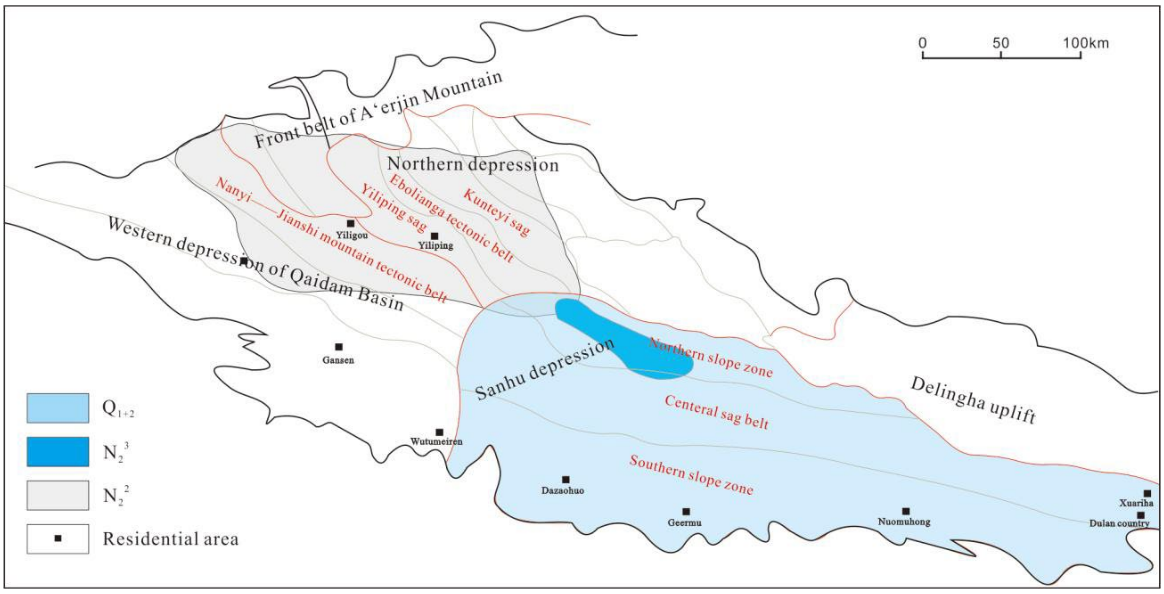

Figure 10. Migration of hydrocarbon generation centers at different times.

5.2. Favorable Zone Prediction

This study found that: (1) N_2^2 and N_2^3 of the Upper Tertiary and Q_{1+2} of the Quaternary are characterized by high mudstone content and no fault communication between the formations. Self-generation and self-storage gas reservoirs were commonly developed. (2) For the exploration of biogenic gas reservoirs in the study area, the burial depth should not exceed 2119 m, and the TOC should not be less than 0.25% in the Quaternary strata and 0.4% in the Upper Tertiary strata. (3) For the exploration of thermogenic gas in the study area, the TOC must be higher than 0.4%, the lower TOC limit of the effective source rocks in the salt lake facies of the western Qaidam Basin [59], and the burial depth of the formation is more than 4000 m, which is likely to produce a large amount of hydrocarbon. (4) In summary, areas that are located near hydrocarbon generation centers with deep burial depths and well-developed traps are likely favorable for oil and gas exploration (Figure 11).

The first favorable exploration zone is the Yahu-Sebei area (Figure 11). The area is close to the N_2^2 hydrocarbon-generating center, and there are deep and large faults connecting the Jurassic source rocks, contributing to the excellent hydrocarbon-generating and migration conditions. In addition, beach-bar sands are well developed in this area with good reservoir physical properties. Many large-amplitude structural traps in the area have been developed, such as the Yahu, Yikeyawuru, Taijinaier, Nanlingqiu, etc. The Yacan-3 well, in particular, produced 610 m^3 of gas per day in the flowing state. The Yishen-1 well obtained industrial gas flow at N_2^3, and gas-logging anomalies occurred five times in the N_2^2 and N_2^3 sections of the Lingshen-2 well in the Nanlingqiu area. It is considered that the petroleum geological conditions in this area are superior, and it is one of the most favorable exploration zones.

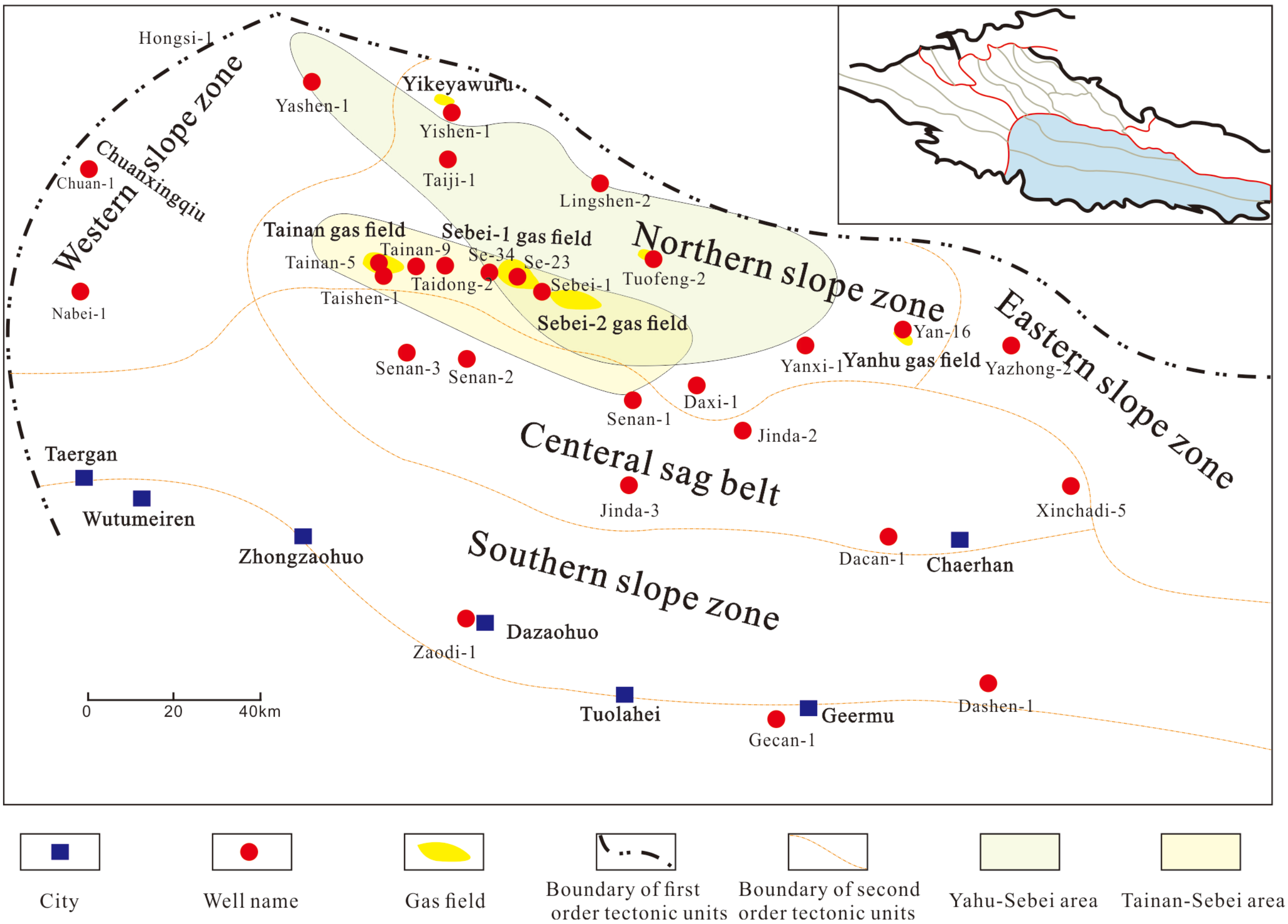

Figure 11. Favorable areas for natural gas exploration in the Sanhu area.

The other favorable exploration zone is the Tainan-Sebei biogenic gas favorable exploration zone (Figure 11). The area is located on the north flank of the Quaternary hydrocarbon-generating center and has good source rock conditions. It is located in a low-potential region of groundwater flow, making it favorable for oil and gas accumulation. The Quaternary reservoir was buried at a shallow depth with good physical properties, which is favorable for oil and gas accumulation. Three biogenic gas fields with huge reserves were found nearby, which confirmed the huge exploration potential of this area.

6. Conclusions and Suggestions

As mentioned above, the depth limits, methane production, and climate impact dominate the biogenic gas accumulation in this area. It is found that N_2^3 and N_2^2 from the Taishen-1 well have no conditions for biogenic gas accumulation but possess "self-generated and self-stored" thermogenic gas. The low abundance and maturity of organic matter serve as the main reasons. As for Q_{1+2}, the main disadvantage of forming a gas reservoir is the rather good geophysical properties of the overlayer and the poor condition of the source rocks, which make it difficult to generate enough gas to form a reservoir. The following understandings were obtained: (1) the lower limit of hydrocarbon generation of TOC in Q_{1+2} is 0.25%, that of the Upper Tertiary is 0.4%, and that of biogenic gas exploration depth is 2119 m; (2) the main reasons for the failure in Q_{1+2} are that the gas production is poor and the gas production is fewer than the needs of reservoir formation; (3) The failure of the Upper Tertiary is mainly due to the poor source rocks, and the TOC fails to reach 0.4%; (4) the Tainan-Sebei area is the favorable exploration area for biogenic gas in the study area, and the Yahu-Sebei area is the favorable exploration area for natural gas in the Upper Tertiary in the study area.

Have shown that more than 70% of the global biogas reserves are distributed in sedimentary environments with low surface (seafloor) temperature and low geothermal gradient conditions, and the abundance of organic matter is usually greater than 0.5% [4], while the organic carbon content of biogas source rocks in the Sanhu area of the Qaidam Basin is between 0.25% and 0.46%. Therefore, the authors suggest that the unique biogas reservoir formation mechanism in the study area be carried out in depth, and its research understanding will be conducive to the exploration and development of biogas reservoirs in other areas with low organic matter abundance in the world.

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