Research Article
Characteristics and Geological Significance of the Hydrocarbon Source Rocks of the Qum Formation in Outcrop of the Northern Garmsar Area, Iran

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The carbonate rocks were collected from the Qum Formation in outcrop of the northern Garmsar Area, Iran. In order to evaluating the hydrocarbon generation prospects of these source rocks, we analyzed their geochemical characteristics, including the abundance, type, and maturity of organic matter, and investigated their formation conditions by analyzing the characteristics of soluble organic matter and sedimentary environment. The results show that the organic matter abundance of the source rocks in the Qum Formation in the Garmsar Area is low in the north and west. The organic matter type is mainly II1-II2, locally showing type I and III, and in general, it is conducive to hydrocarbon generation. The maturity of organic matter is low, showing the $T_{\text{max}}$ between 416°C and 439°C, vitrinite reflectance ($R_o$) from 0.49% to 0.83%, which indicate it is at the stage of low to moderate maturity. The soluble organic matter characteristics indicated that the organic matter evolution of the source rocks in the Qum Formation is low. Through comparison between the study area and other areas, and different places within the working area, the abundance, type, and maturity of organic matter of the source rocks in the Qum Formation are different, caused by the basin facie zones, sedimentary environment, and history of sedimentation of the source rocks. Overall, the source rock in the Qum Formation in Garmsar Area has good prospects of hydrocarbon generation. This study has important significance for further exploration in the Garmsar Area.

1. Introduction

The study of hydrocarbon source rock characteristics has great significance in oil and gas exploration. The quality of source rocks determines the exploration prospects of basins, and the good quality of source rocks is the primary requirement of hydrocarbon generation and accumulation in sedimentary basins [1–4]. Many scholars have provided valuable evidence for determining the exploration prospects of a certain study area, by analyzing of the source rock characteristics. According to the systematic sampling, geochemical analysis, and hydrocarbon generation history simulation of source rocks, Mu et al. [1] and Gang et al. [5] studied the geochemical characteristics of source rocks, evaluated the hydrocarbon generation potential and its expected resource quantity, and suggested the optimization of exploration targets. By analyzing the mineral compositions and their related factors in source rocks, Fu et al. [6] discussed the hydrocarbon geological significance contained in the mineral compositions of source rocks. By using chloroform, methanol-acetone-chloroform ternary reagent, and CS2/NMP super mixed solvent, Zhang et al. [7] studied the binding mode of organic matter in source rocks. The results showed that the binding mode and composition characteristics of organic matter in source rocks that formed in different sedimentary environments are quite different. On the basis of traditional
geochemical analysis, Qin et al. [8] utilized isotopic determination of kerogen and group components to guide oil and gas exploration.

At present, the Qum Formation in the north Garmsar outcrop has a long exploration history. In the 1950s, oil seepage was found in the Gugird Anticline in the southeast of the Garmsar Area. And in the south of it, good shows of hydrocarbon were found in the well TE-1 in the member E of the Qum Formation, which indicated the Qum Formation is a self-generated and self-storage reservoir [9]. By using a detailed interpretation of the reprocessing seismic data from the Shengli Oilfield Company, SINOPEC, Chen et al. [9] analyzed the difference between surface and subsurface tectonics of the Tappeh Pitti Anticline in the Garmsar Area and its formation mechanism. Liu et al. [10] studied the Kuh-i-Gatchab Anticline and concluded that the fractures in the Talkheh and Gatchab anticlines are well-developed with an uneven distribution, which suggested they might be good reservoirs. Xu et al. [11] thought that the pore and permeability conditions of the Qum Formation were poor and showing strong heterogeneity, which belongs to medium to low porosity, and low to extralow permeability reservoirs. From the perspective of sedimentary facies and reservoir characteristics, it was suggested that oil and gas exploration in the Qum Formation has certain risks. By deducing the tectonic activities of the Garmsar Area, during the Oligocene-Miocene, the Qum Formation had a good source-reservoir-seal combination that can form self-generated and self-storage reservoir [12]. Under the influence of thrusting and nappage activities, the fault bending fold or fault spreading fold is produced, which can be served as good oil and gas traps. Wu et al. [13] found that the physical property of the reservoirs in the member E of the Qum Formation in the Garmsar Area generally show low porosity and low permeability, and the deposition environment and diagenesis are the main factors controlling the reservoir development. Considering the extreme heterogeneous of carbonate reservoirs, and the well-developed fractures in the Qum Formation observed in the field, the reservoirs in the member E of the Qum Formation are still likely to be of good quality.

Generally, many scholars have made thorough studies on the characteristics of source rocks and their geological significance. However, previous studies of the Garmsar Area mainly focused on the tectonics and reservoirs, and no systematic studies on the characteristics of source rocks have been made. In this study, we worked on the geochemical characteristics of source rocks and analyzed the hydrocarbon generation conditions and the source rock formation conditions. Combined with reservoir data reported by previous studies, we drew the conclusion that the Garmsar Area has good hydrocarbon generation prospects. The results can provide a theoretical basis for further exploration in this area.

2. Geologic Setting

The Garmsar Block is located in the north-central part of the Central Iran Basin, the north of the Kashan Block, and south of the Varamin-Garmsar-Deh Namak line within the north-western part of the Central Iran Basin, adjacent to the southern foothill of Erbulsh (Figure 1). The western boundary of this block is about 60 km from Tehran, and it forms an irregular trapezoid with a narrow width in the west and wide width in the east. The maximum width from the north to south direction is about 120 km, and the maximum length from the east to west direction is about 130 km, with a proportion of 12183 km². It is a Mesozoic depression basin. Due to the tectonic movements at the end of the Cenozoic, the east, south, and north part of the block were all uplifted into mountains with a nearly east-west direction, while the west part is still covered by the Quaternary strata, which resulted in an extensive exposure of Cenozoic strata. And scattered Mesozoic strata can also be seen in the southern Molkabad Hills and Sefidab areas (Figure 2).

The exploration of this area began in the early 1960s. A few of two-dimensional simulated seismic and gravitational and magnetic surveys have been carried out, and a number of structural traps have been found. On this basis, anticlines such as South Siah-Kuh, East Talkheh, and Tappeh Patti were discovered. And well SSK-1 and well TE-1 were drilled in South Siah-Kuh anticline and East Talkheh anticline, respectively. The well SSK-1 is located at the high ground of the South Siah Kuh anticline. The drilling began in July 1964 and was completed on April 29th, 1965. The well starts from the member M1 in the URF Formation, ends in the member M1 in the URF Formation at the depth of 3983.4 m, and failed to reach the target strata of the Qum Formation. The well TE-1 is located in the north side of the East Talkheh Anticline. The drilling began on February 14th, 1961, and was completed on June 14th, 1962. This well was mainly drilled through the member M1, the member M1 in the URF Formation, the Qum Formation, and the pre-Qum Formation (Figure 2). A small amount of oil and gas (5% oil-bearing water layer) was obtained in the member E of the Qum Formation, with a daily oil production of 40 t, indicating that the Garmsar Area of Iran has good hydrocarbon source conditions.

3. Samples and Methods

The rock samples in this study are mainly collected from the outcrop area in the north part of the study area (Figure 3), with a total of 53 blocks. The strata we collected the samples are in the member C and E in the Qum Formation, and the lithology is mainly limestone and marlrite. Total organic carbon (TOC) and Rock-Eval pyrolysis analysis data were carried out using a LECO CS-230 carbon sulfur analyzer and Rock-Eval 6 pyrolysis, respectively. During the experiments, the samples were analyzed at a constant temperature of 300°C for 3 min to obtain S1 (free hydrocarbon) and heated at a heating rate of 25°C/min between 300 and 650°C to obtain S2 (pyrolysis hydrocarbon). The gas chromatography-mass spectrometry (GC-MS) experimental conditions, instrument, and compound quantitative method were provided by Jiang et al. [14] and Li et al. [15].
4. Results and Discussion

4.1. Geochemical Characteristics of Source Rocks

4.1.1. Abundance of Organic Matter. The abundance of organic matter is the most basic index for the evaluation of source rocks. There are relatively unified evaluation standards of muddy hydrocarbon source rocks in the oil industry. However, when it comes to carbonate source rocks, there is a great controversy over their evaluation criteria. Researchers and institutions from the globe have put forward different evaluation criteria for the lower limit value of carbonate source rocks. The main differences are the age of source rocks, the type of parent materials, and the degree of thermal evolution. In this study, we used evaluation criteria put forward by Qin et al. [16] for carbonate source rocks (Table 1), which is based on hydrocarbon expulsion simulation experiment and actual evolution profile of source rocks. These evaluation criteria of carbonate source rocks are put forward by taking the worldwide classification criteria of hydrocarbon source rocks and statistics of organic carbon in carbonate oil and gas fields as references, and in line with the classification of source rocks according to hydrocarbon generation potential and soluble organic matter (immature to mature stage). The main parameters are organic matter abundance, type, and maturity.

The amount of organic matter preserved in sediments depends on the organism’s development and its depositional environment. Organic matter can be preserved in large quantities in low energy, anoxic, inhibited stagnation of bacterial activity, and closed basins. On the contrary, dry, high-energy, oxygen-rich environments intensify the biological and chemical degradation of the organism, which is causing difficulties in preserving organic matter [17]. The content of organic matter in sedimentary rocks is the material basis for determining hydrocarbon production, and the maturity of organic matter is an important indicator to measure the actual hydrocarbon generation capacity of source rocks. The geochemical indicators that characterize the abundance of organic matter include TOC content in rocks (%), chloroform bitumen “A” (%), and hydrocarbon generation potential.

The results of the geochemical analysis of the rock samples in the outcrop show that the abundance of organic matter is low, with TOC values less than 0.30%, between 0.04% and 0.27%. Among these samples, only 20% samples have organic carbon content higher than 0.1% (Figure 4), with an average of 0.07%. The hydrocarbon generation potential is 0.01-0.26 mg/g, and 90% samples have hydrocarbon generation potential less than 0.1 mg/g, with an average of 0.03 mg/g. In vertical, the organic matter abundance of the member Qum-E rock samples is generally higher than that of the member Qum-C (Table 2). In horizontal, the organic matter abundance of rock samples in the outcrop area is higher in the east than that in the west and higher in the south than that in the north. For example, the profile V in the west (Figure 3) has the highest organic matter abundance, followed by the profile II in the north (Figure 3). As for the profiles in the east, the organic matter abundance is generally low (Table 2).

4.1.2. Type of Organic Matter. The type of organic matter is an important indicator of source rock quality evaluation. Since different types of organic matter have significantly different hydrocarbon generation potentials, the accurate determination of organic matter types in source rocks is very important for evaluating and predicting the prospects of oil
and gas exploration in a certain region. The identification results of kerogen are generally based on microscopy, supplemented by other methods. However, for carbonate rocks, the types of organic matter in carbonate rocks are controlled by sedimentary facies. Traditionally, it is believed that marine carbonate mainly has a single type of organic matter, usually the hydrogen-rich type I. In the practice of evaluating the hydrocarbon generation potential of carbonate in China, the influence of the transformation and preservation conditions of the organic matter during the initial deposition period was usually neglected. Therefore, the organic matter in carbonate cannot be simply divided into type I or type II kerogen. Instead, when determining the types of organic matter, the changes of sedimentary and organic facies in
carbonate also should be considered. Take the pre-Devonian organic matter as an example, although the biogenic source was completely fungi and algae, the hydrocarbon generation capacity of some type of kerogen may only be equivalent to that of humic kerogen (type III). In this study, the determination of organic matter types was made based on the whole rock microscopic observation, identification, and pyrolysis parameters.
Like other carbonate source rocks, the kerogen micro-
composition of the outcrop samples in the northern Garmsar
Block is dominated by the sapropel group with strong hydro-
carbon generation ability. Among the analyzed six samples,
extcept one sample that shows a low content of the sapropel
group (i.e., 69%), the contents of the sapropel group in other
samples are all above 95%, and the type index is above 90
(Table 3), which marks a good organic matter type.

The microscopic observation shows that the source rocks
of the Qum Formation are mainly composed of inorganic
minerals. The organic macerals only take up 0-0.3%, mainly
include the asphaltene and algae debris, followed by some
shell debris. This indicates that although the content of
organic matter in the rock sample is low, there were low-
grade aquatic organisms in the water during the deposition.
These aquatic organisms were poorly preserved in the
sedimentary environment of the outcrop but may be much
abundant in the deeper part of the water (Table 4). Accord-
ingly, it can be seen that the types of organic matter should
be mainly type I-II. However, decomposed animal organic
matter and mineralized debris are also found in the rock
samples, likely indicating that during the sedimentary of

| Evolution stage | Organic matter type | Index | Excellent source rock | Good source rock | Moderate source rock | Bad-non source rock |
|-----------------|---------------------|-------|-----------------------|------------------|---------------------|-------------------|
| Immature–mature | I-II₁               | TOC (%) | >2                    | 1.0-2.0          | 0.3-1.0             | <0.3              |
|                  | S₁ + S₂ (mg/g rock) |       | >10                   | 5-10             | 2.5                 | <2                |
|                  | II                  | TOC (%) | >3.0                  | 1.5-3.0          | 0.5-1.5             | <0.5              |
|                  | S₁ + S₂ (mg/g rock) |       | >10                   | 5-10             | 2.5                 | <2                |
| High–over mature | I-II₁               | TOC (%) | >1.5                  | 0.7-1.5          | 0.2-0.7             | <0.2              |
|                  | II                  | TOC (%) | >2.5                  | 1.2-2.5          | 0.4-1.2             | <0.4              |

Table 1: Classification criteria for carbonate source rocks (according to [16]).

| Location          | Profile | Sample numbers | Segment | TOC (%)    | Potential of hydrocarbon generation (mg/g rock) | \( T_{\text{max}} \) (°C) |
|-------------------|---------|----------------|---------|------------|-----------------------------------------------|---------------------------|
| Northeast part    | 1       | 12             | Qum-C   | 0.04-0.06  | 0-0.01 (0.003)                                | 416-461                   |
|                   | 2       | 2              | Qum-E   | 0.03-0.17  | 0-0.07 (0.035)                                | 416                       |
|                   | 7, 9    | 5              | Qum     | 0.03-0.05  | 0.01                                          | 438                       |
|                   | 8       | 8              | Qum-C   | 0.04-0.23  | 0-0.18 (0.05)                                | 433-439                   |
| North part        | 2       | 1              | Qum-E   | 0.16       | 0.1                                           | 437                       |
|                   | 4       | 2              | Qum     | 0.04       | 0.01                                          | 416                       |
|                   | 3       | 3              | Qum-C   | 0.06-0.07  | 0.01-0.02 (0.015)                             | 450                       |
|                   | 14      | 2              | Qum-E   | 0.04-0.07  | 0.01                                          | 426-460                   |
|                   | 5       | 2              | Qum     | 0.12-0.27  | 0.03-0.26 (0.15)                             | 428-431                   |

Table 2: Statistical table of organic matter abundance of outcrop samples in northern Garmsar Block.

Figure 4: Frequency distribution diagram of rock organic matter abundance in the Qum Formation in the northern Garmsar Block.
the Qum Formation in the northern Garmsar Area, a turbulent marine environment caused the poor preservation conditions of organic matter.

It is convenient and quick to determine the types of organic matter in rocks based on the relationship between pyrolysis parameter $T_{\text{max}}$ and IH. However, due to the error in $T_{\text{max}}$ of rocks with low organic matter abundance, other parameters should be considered comprehensively to determine the organic matter type in this case. It can be seen from the $T_{\text{max}}$-IH diagram that the selected Qum Formation rock samples from the northern outcrop area mainly fall into the range of organic matter type II$_{1−3}$ (Figure 5), reflecting poor hydrocarbon generation ability.

The input of organic matter in marine sediments is mainly plankton, which is generally thought to be the biological precursor of type I organic matter. However, modern marine geochemical studies have shown that the same biological precursors under oxygenation conditions can form hydrogen-poor and oxygen-rich humus by marine humification. That is because the oxygen-rich environment caused the loss of organic functional groups and the increase in the aromatic nucleus and the oxygen content. Carbonate deposits, especially relatively pure carbonate deposits, are mostly products of high-energy, oxygen-filled shallow sea environments. Organic matter derived from planktonic algae, zooplankton, and benthic algae may be transformed into humic-like organic matter through marine humification under such conditions. It should be pointed out that the biological organic matter of some benthic algae in the ocean is inherent "humus" with low protein, low-fat content, and rich carbohydrates, and the kerogen derived from it is also hydrogen-poor. In addition, the identification of the organic matter types of rock samples in the outcrop area may be affected by the storage conditions and the effects of surface weathering.

4.1.3. The Maturity of Organic Matter. The maturity of organic matter determines the characteristics of hydrocarbons generated by the thermal evolution of source rocks. Therefore, the demarcation of maturity is of great significance in the evaluation of effective source rocks, the evaluation of oil and gas resources, and the direction of future explorations. Vitrinite reflectance ($R_v$) is the most important maturity index for the study of organic matter thermal evolution stages in source rocks [18, 19], and most of the other indexes are demarcated based on the $R_v$ value.

In this study, the determination of the maturity of rock samples in the northern outcrop area of the Garmsar Block is based on the vitrinite reflectance, combined with the pyrolysis peak $T_{\text{max}}$ and whole-rock petrographic observation. The results of vitrinite reflectance analysis showed that the evolution of organic matter was low, ranging from 0.49% to 0.83%, and is generally in the low mature stage to the early-middle mature stage. From the plane distribution perspective, the northwest (represented by profile II in Figure 3) has the lowest maturity, with $R_v$ values between 0.49% and 0.66%, and close to the maturity threshold value. And then, the northeast part (represented by profile I in Figure 3) has a $R_v$ value of 0.71% which indicates an early stage of maturity. The western part (represented by profile XIV in Figure 3) has a relatively high degree of evolution, with $R_v$ value ranging from 0.78% to 0.83%, indicating the early to middle stage of maturity evolution.

The pyrolysis peak $T_{\text{max}}$ of the rock samples is between 416 and 462°C (Figure 5). Since the pyrolysis $S_2$ value of the rock sample is very low (generally less than 0.04 mg/g), the credibility of the $T_{\text{max}}$ value is reduced. The pyrolysis peak $T_{\text{max}}$ of samples with relatively high $S_2$ values is between 416 and 439°C, so the rock samples in the outcrop area are in the low mature to mature stage. Also, according to the microscopic observation, the fluorescence of the algal fragments is yellow, and it suggests the maturity is not very high.

4.2. Analysis of Hydrocarbon Generation Conditions in Source Rocks. The Garmsar Block is a subdepression located in the east of the sedimentary center that preserved a complete Qum Formation. Drilling confirmed that the thickness of the Qum Formation on the Talkheh structure is more than 750 m (Figure 6). The abundance and mass of organic matter in marine carbonate source rocks are mainly influenced by the sedimentary environment. Just like mudstone, the potential of carbonate mainly depends on the organic phase, rather than the mineral matrix. When the sedimentary environment is strongly oxidized, the total organic carbon content is low. In anoxic sedimentary environment, organic-rich fine-grained carbonates can be formed. And these deposits are the potential source rocks, generally carbonate rocks with laminae and high organic carbon content. Therefore, it is important to study the sedimentary environment of carbonates and look for facies belts that are conducive to the accumulation and preservation of organic matter. The common sedimentary environment model of carbonate rocks is

| Simple name | Sampling site | Formation | Sapropel % | Exinite % | Vitrinite % | Inertinite % | Type | Type index |
|-------------|--------------|-----------|------------|-----------|-------------|-------------|------|------------|
| 1-S18-2     | Outcrop      | Qum       | 69.0       | 0.0       | 29.0        | 2.0         | III  | 45.3       |
| 2-S13-1     | Outcrop      | Qum       | 95.3       | 0.0       | 4.7         | 0.0         | I    | 91.8       |
| 2-S16-2     | Outcrop      | Qum       | 96.7       | 0.7       | 2.7         | 0.0         | I    | 95.0       |
| 2-S22-2     | Outcrop      | Qum       | 96.7       | 0.0       | 3.3         | 0.0         | I    | 94.2       |
| 14-S7-1     | Outcrop      | Qum       | 96.3       | 0.0       | 3.7         | 0.0         | I    | 93.6       |
| 14-S16-1    | Outcrop      | Qum       | 98.3       | 0.0       | 1.7         | 0.0         | I    | 97.1       |
Table 4: Data of the Qum Formation rock in the north of Garmsar block.

| Profile | Formation | Structural alga | Sapropel alga | Nonstructural alga | Bituminite | Spore powder+cutinite+resinite+suberinite | Shell crumbs | Vitrinite | Inertinite | Secondary components | Animal organic detritus | Mineral asphalt matrix | Inorganic mineral |
|---------|-----------|----------------|---------------|--------------------|------------|------------------------------------------|--------------|-----------|------------|---------------------|-----------------------|-------------------------|------------------|
| No.1 Qum | 0         | 0              | 0.1           | 0.2                | 0          | 0                                        | 0             | 0         | 0.1        | 0                   | 0                     | 0                      | 99.6            |
| No.7 Qum | 0         | 0              | 0.1           | 0.1                | 0          | 0                                        | 0             | 0         | 0.1        | 0                   | 0                     | 0                      | 99.9            |
| No.9 Qum | 0         | 0              | 0.1           | 0.1                | 0          | 0                                        | 0             | 0         | 0.1        | 0                   | 0                     | 0                      | 99.6            |
| No.2 Qum | 0         | 0.1            | 0.1           | 0.2                | 0          | 0                                        | 0             | 0         | 0.1        | 0                   | 0                     | 0                      | 99.5            |
| No.4 Qum | 0         | 0              | 0.1           | 0.1                | 0          | 0                                        | 0             | 0         | 0.1        | 0                   | 0                     | 0                      | 99.6            |
| No.5 Qum | 0         | 0.1            | 0.1           | 0                  | 0          | 0                                        | 0             | 0         | 0.1        | 0                   | 0                     | 0                      | 99.7            |
| No.14 Qum | 0        | 0              | 0.1           | 0                  | 0          | 0                                        | 0             | 0         | 0.1        | 0                   | 0                     | 0                      | 99.7            |
characterized by the abrupt change from shallow water shelf to deep water basin. The sedimentary environments in which carbonate source layers develop mainly include the following: (1) near-shore system: composed of mud and granular sediments, coastal lagoons can form good source rocks. (2) Platform sag system: characterized by low-energy plastr, good source rocks can be formed. (3) Platform edge system: it is characterized by the oolitic beach or bone debris deposited under high-energy and turbulent environment, no hydrocarbon source rocks developed here. (4) Platform slope system: the sedimentary systems of platform slope and fore-reef are featured by the gradual decrease of particles and the gradual increase of mud in the direction of the lower part of the slope, and the hydrocarbon source rocks are well developed. (5) Basin system: the carbonate rock system in the basin is dominated by plaster and the source rocks are well developed.

During the deposition period of the Qum Formation, due to the favorable climate, the organism flourished. Meanwhile, the relatively deep water environment, which was below the wave base, is conducive to the preservation of organic matter, resulted in a relatively high organic matter content and a high hydrocarbon generation potential. In 1961, The Iranian Oil Ministry has completed the drilling of the well TE-1 in the Talkheh structural belt. 37 rock samples of the member Qum-E were analyzed, and the result showed that samples from member Qum-E were high in the abundance of organic matter. 50% of these samples had an organic carbon content higher than 0.3%; among them, 5% of samples with TOC content are higher than 1.0%, with an average of 0.51% and a highest of 2.37% (Figure 7). The organic matter abundance values of these samples are much higher than those in the outcrop area. Up to 51.4% of the tested samples had a hydrocarbon generation potential higher than 0.5 mg/g and 9% higher than 2 mg/g, and the highest value can reach up to 6.78 mg/g. In vertical, the deep part of the member Qum-E has a relatively high abundance of organic matter, with the dominated type II organic matter. The $T_{\text{max}}$ values are between 431 and 439°C, and the thermal evolution stage is in low-mature to mature stage. The comprehensive evaluation suggests it is a set of medium to good source rocks, and in some parts, it can reach the evaluation standard of excellent source rocks, which is better than the rock samples from the northern outcrop area.

There are differences in abundance and types of organic matter between well TE-1 and outcrop area. Two possible reasons are listed as follows: the first is the effect of primary organic matter, deposition rate, sedimentary environment, and preservation conditions, that is, the influence of sedimentary facies. Although the abundance of the original organic matter in the sedimentary body is not the most sufficient reason to form the original organic-rich source rocks, it still influences the organic matter abundance of source rocks. The abundance of original organic matter in the sedimentary body is conducive to increasing the content of organic matter in the source rocks. Moreover, the reduction of excess organic matter can create an anoxic environment at the bottom of the water, which is conducive to the preservation of organic matter. Accordingly, the final accumulated organic components become organic matter in potential source rocks. During the deposition of source rocks, the depth of the bottom water is not the only condition for the development of organic-rich sediments, and the preservation condition mainly depends on the oxygen content at the bottom of the water. The oxygen content of water depends on many factors such as water depth, sedimentation rate, abundance of original organic matter in sediments, the disturbance degree of bottom water, and the limitation degree of water. Source rocks are typical fine-grained and thin-layered sedimentary rocks lacking traces of biological agitation, which are in sharp contrast with strong biological agitation shale, marl, and carbonate mud developed under normal oxidation conditions at the bottom of water body. According to this theory, the inland basin should be the most favorable place for the deposition of carbonate oil and gas. Under the same conditions of other factors, with the increase of the basin, the oxygen content of the sedimentary water will eventually change from a primitive anaerobic basin to an oxidation basin. This is the reason why the source rocks in carbonate oil and gas. Under the same conditions of other factors, with the increase of the basin, the oxygen content of the sedimentary water will eventually change from a primitive anaerobic basin to an oxidation basin. This is the reason why the source rocks in carbonate oil and gas fields are mostly located in inland basins. The second is the effect of surface secondary processes, including surface temperature, especially the range of temperature difference, scouring of surface water and wind, infiltration and oxidation of surface water, length of exposure to the surface, different lithology, activities of surface plants, animals or human beings, and organic acids in the roots of surface plants.

The Qum Basin is a NW-SE-oriented narrow basin (Figure 1) adjacent to the study area. The Qum Formation is a set of marine carbonate platform facies sedimentation, stably located in the whole Qum Basin. The thickness of the member Qum-E and Qum-C in Alborz Oil Fields and

![Figure 5: IH – $T_{\text{max}}$ diagram of the Qum Formation in the northern Garmsar Block.](image-url)
Sarajeh Condensate Gas Fields in the central Qum Basin is over 1200 m. The TOC values of rock samples in the Qum Formation are between 0.1% and 0.93%, and the values of the member Qum-E are mainly from 0.3% to 0.5% with an average of 0.45%. The TOC values of the member Qum-E rock samples from the two areas are higher than 1.0%.
For the member Qum-C of the two areas, the TOC values are both less than 1.0% and range from 0.1% to 0.3%, with the average of 0.2% and 0.41%, respectively. According to the geochemical profiles of the two places, the abundance of organic matter in the member Qum-E is higher than that in the member Qum-C. In Sarajeh Condensate Gas Field, the higher organic matter abundance in the member Qum-E is located in the depth of the middle and lower part.
while in the Albroz Oil Field, the higher organic matter abundance of the member Qum-E are in the depth of the middle parts. As for the member Qum-C of the two fields, the high abundance of organic matter is mainly distributed in the upper part. The type of organic matter is mainly II and the $T_{\text{max}}$ values are between 426 and 449°C, which indicates the organic matters are in the mature stage.

In the outcrop around the Kashan Block in the southern Qum Basin, rock samples are of low organic matter abundance and TOC values are generally lower than 0.12%, indicating they are non/bad hydrocarbon source rocks. The types of organic matter are from I to III, and the thermal evolution is mainly in the mature stage. In some areas, due to the influence of igneous rocks, the thermal evolution in some areas reaches the high maturity stage and the hydrocarbon generation potential is limited. The organic carbon contents of rock samples in the wells of the Kashan Block are generally less than 1.0%.

### Table 5: Comprehensive evaluation table of source rocks in the Qum Basin.

| Location | Well | Member | TOC (%) | $S_1 + S_2$ (mg/g rock) | $T_{\text{max}}$ (°C) | Organic matter type | $R_o$ (%) | Evaluation result |
|----------|------|--------|---------|-------------------------|------------------------|---------------------|-----------|------------------|
| FKh-1    | Qum-E| 0.27-0.47 | 0.15-1.32 | 432-445 | I-II | 0.54-0.59 | Bad-moderate |
| FKh-1    | Qum-C| 0.04-0.08 | 0.01-0.06 | 436-439 | | | Non |
| Arn-1    | Qum-E| 0.07-0.28 | 0.09-0.18 | 428-446 | I-II | 0.64-0.67 | Bad-non |
| Arn-1    | Qum-C| 0.11-0.16 | 0.06-0.10 | 439 | I-H | | Non |
| Kashan   | Arn-1| 0.09-0.41 | 0.15-0.66 | 416-430 | II-III | 0.42-0.46 | Bad-moderate |
| Arn-1    | Qum-C| 0.1-0.92 | 0.73-1.32 | 428-429 | III-I | | Bad-moderate |
| Arn-2    | Qum-E| 0.16-0.23 | 0.06-0.21 | 429-430 | | | Bad-non |
| Arn-3    | Qum-E| 0.14-0.16 | 0.03-0.05 | 430-435 | | | Bad-non |
| Outcrop  | Qum-E| 0.04-0.12 | 0.001-0.006 | 412-451 | I-III | 0.75 | Bad-non |
| Sarajeh  | Qum-E| 0.10-0.93 | 0.1-4.63 | 430-449 | II-I- | 0.71-0.79 | Moderate |
| Qum      | Qum-C| 0.10-0.92 | 0.1-3.09 | 434-450 | II-I- | | Moderate |
| Alborz   | Qum-E| 0.14-1.41 | 0.2-4.6 | 437-442 | II-I- | 0.78-0.82 | Bad-good |
| Outcrop  | Qum-C| 0.04-0.98 | 0.16-2.21 | 440-443 | II-I- | 0.84-0.85 | Bad-moderate |
| Qum      | Qum-E| 0.08-0.41 | 0.007-0.414 | 416-425 | II-I- | 0.51 | Bad-moderate |
| Garmsear | Qum-C| 0.03-0.07 | 0.004-0.01 | 416-475 | II-I- | 0.7 | Non |
| TE-1     | Qum-E| 0.12-2.37 | 0.13-6.78 | 431-438 | II | 0.48-0.49 | Bad-excellent |
| Outcrop  | Qum  | 0.02-0.27 | 0.01-0.26 | 418-442 | II-I- | 0.49-0.83 | Bad-non |
and 10). The TOC values of some individual samples of the member Qum-E in well Fkh-1 are higher than 1.0%, with the type I-II organic matter, and organic matter has entered the mature hydrocarbon generation threshold. According to the geochemical profiles of the well Fkh-1 and Arn-1, like other areas, the organic matter abundance of the member Qum-E is higher than that of Qum-C. And the higher organic matter abundance of the member Qum-E is located at the lower part, while the upper part of the member Qum-C has higher organic matter abundance.

According to samples from outcrops and wells in the member Qum-E and Qum-C (Table 5), the organic matter abundance gradually gets higher from south to north. However, there are some differences in different sedimentary facies in different areas.

In addition, the vitreous reflectance (Rv) analysis results of more than 20 samples in the Qum Basin (Figure 11) show that the values in the Qum Formation are between 0.4% and 0.9%, mainly at the stage of low-mature to mature. However, from the perspective of the distribution of organic matter evolution in the Qum Formation, there is a strong imbalance in both lateral and vertical. The difference in organic matter thermal evolution of different regions was significant. The Kashan area has a relatively low maturity, with a burial depth over 3,000 m and Rv about 0.45%-0.64%, which is in the early stage of maturity. In the central Qum Basin, the maturity is relatively high, at 2500-3500 m, and Rv has reached about 0.7%-0.9%, reaching the peak of hydrocarbon generation in the mature stage. As for the well TE-1 in the Garmsar Area, burial at the depth of 1300-2000 m, and Rv has reached 0.5-0.6%, just entered the stage of liquid hydrocarbon generation.

Overall, the Qum Formation in the Garmsar Area is a set of medium to good hydrocarbon source rocks with dominated type II organic matter and low maturity to mature evolution. Some parts have excellent development of hydrocarbon source rocks and good potential of hydrocarbon generation. And the sedimentary facies mainly controlled the distribution of source rocks.

![Figure 11: Rv distribution frequency diagram of rock samples from the Qum Formation in the Qum Basin.](image)

### 4.3. Analysis of Source Rock Formation Conditions

#### 4.3.1. Characteristics of Soluble Organic Matter

The composition characteristics of organic solvent components of source rocks are the indicators that reflect the organic matter composition, which is usually represented by the characteristics of chloroform bitumen extracts, mainly including the content of chloroform bitumen, group composition characteristics, saturated hydrocarbon, and aromatic hydrocarbon fraction composition characteristics. The composition characteristics of soluble organic matter are important bases for oil source correlation and source rock evaluation.

The chloroform bitumen contents of the samples collected in this study are very low, ranging from 0.0011% to 0.0065%. The reasons are likely (1) low organic matter abundance in the samples. (2) The sedimentary environment of carbonate had low clay content, resulting in poor adsorption capacity for soluble organic matter. (3) Samples taken from the ground surface are affected by weathering degradation. Because of the low content of chloroform bitumen, its extract is insufficient for the group composition and isotopic composition analysis. The soluble organic matter was mainly analyzed by the composition of saturated hydrocarbon and aromatic hydrocarbon fraction, and the samples analyzed are mainly those with high organic matter abundance and chloroform asphalt extracts.

The m/z 217 mass chromatogram shows that the evolution degree of organic matter is very low, the C27, C28, and C29 regular sterane isomerization parameter 20S/(20S+20R) C29 sterane is only 0.10, and the ββ/(αα+ββ) C29 sterane is 0.13, indicating the organic matter is in the immature stage (Figure 12). The main component of the steranes is the regular steranes, while contents of pregnanes and diasteranes are very low. Regular steranes were distributed in irregular “V” shape, and the proportions of C27, C28, and C29 regular steranes were 37%, 15%, and 48%, respectively, which indicated the input of the algae and advanced plants.

The distribution of terpene is similar to sterane (Figure 12). Many compounds that can only exist or be abundant at low maturity have a relatively high content in the chromatogram, such as 17β-C27 trisnorhopane and ββ hopane. The contents of tricyclic terpane and tetracyclic terpane are generally low, and the dominating compound is the pentacyclic terpane. In the composition of a single terpane compound, the relative contents of Ts and gammacerane are relatively low, the Ts/Tm value is 0.06, and the gammacerane index is 0.11. The relative content of 22S and 22R type in homohopane shows that 22R is greater than 22S. There is a decreasing variation trend from C31 homohopane to C35 homohopane in m/z 191. The abundance of C34 and C35 homohopane is very low in the freshwater environment. High abundance C34 and C35 homohopane is the feature of high salinity and strong reduction environment. According to this, it is obviously not the case of the northern Garmsar Block.

Aromatic hydrocarbon is more stable than sterane and terpane. It reflects the structure and properties of crude oil and its source materials, and it also can determine the evolution degree of organic matter. Therefore, aromatic
hydrocarbon can be used as important markers in the study of organic matter characteristics. The content of the phenanthrene series compound was the highest in the aromatic hydrocarbon in the northern Garmsar Block, followed by triaromatic sterane, and the naphthalene series is relatively low in content. According to the maturity index of phenanthrene series compounds, the calculated vitrinite $R_c$ is 0.59% ($R_c = 0.55\text{MPI1} + 0.44$, Radke et al., [20]), slightly higher than the measured vitrinite reflectance value of rock samples, indicating it is in the early stage of maturity. The source of triaromatic sterane is similar to that of sterane. The relative content of short side chain triaromatic sterane is very low, while in the long side chain triaromatic sterane, the content of $C_{28}$ triaromatic sterane is the highest, followed by $C_{26}$ and $C_{27}$ triaromatic sterane.

4.3.2. Sedimentary Environment. During the late Oligocene to early Miocene, the study area evolved into an extensional basin under the compression. Seawater invaded from the southwest, and the Qum Formation was deposited in two major sedimentary cycles, and each ended with evaporite. During the deposition period of the Qum Formation, the climate is warm, the water is shallow, the flow is smooth and energy is medium, the salinity is normal, and the biological species is diverse, which are all conducive to the development of organic matters. Two sets of sea transgressions and regressions happened during the Qum Formation deposition, forming the member Qum-E and Qum-C, which were the two main hydrocarbon source rocks in the basin.

The Qum Formation in this work area is mainly composed of mixed carbonate rocks and terrigenous clasts, which belongs to the sedimentary environment of the mixed water carbonate rocks platform. The lithologies of the member Qum-E and Qum-C are mainly bioclastic carbonate, argillaceous carbonate, and calcareous or dolomitic clastic rock. The possible source rocks are mainly argillaceous carbonate, calcareous and dolomitic clastic rock. In summary, the source rocks in outcrops of the member Qun-E and Qum-C are not well developed (Table 6), and the overall environment is a shallow-water and high-energy environment where bioclastic rocks are generally developed.

Since the samples in this area were taken from outcrops, the soluble organic matter and hydrocarbon generation potential ($S_1 + S_2$) were greatly affected by surface weathering.

| Profile | Member | Possible source rock thickness/m | | Total thickness of interval/m | Proportion of possible source rocks/% |
|---------|--------|---------------------------------|---|-----------------------------|-------------------------------------|
| No.1    | Qum-C  | Argillaceous carbonate 29.06    | 20.75 | 84.49 | 58.95 |
|         | Qum-E  | 6.92                            | 53.53 | 142.44 | 42.44 |
| No.2    | Qum-C  | 9.22                            | 32.84 | 104.37 | 40.30 |
|         | Qum-E  | 9.29                            | 22.84 | 84.55 | 38.00 |
| No.14   | Qum-C  | 17.72                           | 45.53 | 141.51 | 44.70 |
|         | Qum-E  | 36.19                           | 45.75 | 126.03 | 65.02 |

Figure 12: Chromatogram of saturated hydrocarbon fraction of outcrop samples in northern Garmsar Block (upper m/z 191, lower m/z 217).

Table 6: Potential source rocks of the Qum Formation in the northern outcrop of the Garmsar Block.
and the maturity. The residual organic carbon was relatively less affected by weathering and was easy to be accurately determined, which means it still can be used as a basic index for evaluating the quality of hydrocarbon source rocks [16]. Overall, the Qum Formation in the north of the Garmsar Block is a set of low-mature to mature non/bad hydrocarbon source rocks with limited hydrocarbon generation capacity and no material basis for industrial oil flow. The organic matter abundance increases from east to west and north to south.

5. Conclusions

(1) Field data analysis indicated that the organic matter abundance of source rocks of the Qum Formation in the Garmsar Block was low in the north and west. Laterally, the outcrop sample’s organic matter abundance is higher in the east than that in the west and higher in the south than that in the north.

(2) According to the whole rock and microscopic observation of the outcrop samples, organic matter types of the Qum Formation source rocks are mainly type I-II2. Based on the rock pyrolysis, the organic matter types are type II2-III. Combining with the data of adjacent areas and drilling samples, the Qum Formation organic matter types should be relatively good, mainly type II1-II2, locally type I, and type III.

(3) The evolution of the organic matter in Qum Formation source rock samples is relatively low, with Tmax between 416 and 439°C and R0 between 0.49% and 0.83%, which indicate it is at the stage of low to moderate maturity. Laterally, the northwest part has the lowest degree of evolution and close to the maturity threshold. And it is followed by the northeast part, which is in the early stage of maturity. The west part is relatively high and is in the early and middle stage of maturity.

(4) The characteristics of soluble organic matter of the source rocks in the Qum Formation indicated the evolution of organic matter is low, and the sedimentary environment was different from that of the pure marine carbonate.

(5) Overall, the Qum Formation in the Garmsar Area has a set of type II organic matter, low-mature to mature source rocks. In some local parts, it has excellent development of hydrocarbon source rocks and good potential of hydrocarbon generation.

Data Availability

The data are shown in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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