ABSTRACT: The Lower Jurassic reservoir has recently made a significant breakthrough in petroleum exploration in the Tugerming area of the eastern Kuqa depression, Tarim Basin, northwest China. Therefore, it is significantly essential to simulate the hydrocarbon charging process and analyze the accumulation mechanism in the study area. In our study, we mainly combine three geochemical techniques to identify the origin of crude oils and fluid inclusion characteristics in the target well (Tudong 2), including gas chromatography–mass spectrometry (GC–MS), comprehensive two-dimensional GC-time-of-flight MS (GC × GC–TOFMS), fluid inclusion analysis, and quantitative fluorescence technique. Combined comprehensive experiments with a set of burial history and tectonic thermal evolution history realize the reconstruction of the hydrocarbon charging process in the Yangxia formation. The results show that Jurassic coal-bearing source rocks are primary hydrocarbon sources, and there are three hydrocarbon charging events in the Lower Jurassic reservoir. First, the mature oils have expelled into the reservoir during the early-middle period (15−10 Ma) of the Miocene Kangcun Formation, forming yellow fluorescent oil inclusions and most of the quantitative grain fluorescence (QGF) indexes exceed 4. Second, numerous condensate oils have charged into the reservoir in the period of late Miocene Kangcun Formation–early Kuqa Formation (9−6 Ma), accompanied by blue-white oil inclusions and QGF on extract intensity greater than 4. Finally, vast natural gas has accumulated in the reservoir since Kuqa Formation (5−0 Ma), resulting in the adjustment of ancient reservoir and residual bitumen. Interestingly, we find that the hydrocarbon accumulation mechanism is characterized by self-generation and self-storage in the Jurassic Yangxia Formation, and the study area has prominent characteristics of late accumulation. Thus, the evidence obtained from our analysis suggests favorable geological conditions for the formation of a large oil and gas reservoir in the eastern Kuqa Depression.

1. INTRODUCTION
The Tarim Basin, located in the northwest of China, is an important hydrocarbon-producing basin, bordered by the Tianshan mountains to the north and the Kunlun and Altun mountains to the south, which covers an area of approximately 560,000 km².1 The Kuqa Depression is located in the northern Tarim Basin and acted as a foreland basin developed since Miocene.2 It is a narrow east−north−east trending depositional basin caused by the remote effects of the India−Asia collision, with an exploration area of 28,000 km².3 It has experienced multiple periods of tectonic activities and intense structural deformation, resulting in five belts and three sags in the depression, characterized by “north−south zoning, east−west segmenting”.4 In addition, there are several lateral and horizontal compressional nappe structures, such as forward-spread thrust structures and various fault-related folds. In the past decade, significant breakthroughs have been made in the oil and gas exploration in the Kuqa Depression, such as discovering several giant and medium-sized gas fields in the Kelasu-Yiqikelike and Qulitake structural belts. The Tugerming area is our research target, located in the eastern Kuqa Depression (Figure 1). Recently, industrial oil flow output from the Jurassic Yangxia Formation of Well Tudong 2 in the eastern Tugerming area has been observed, showing a grand promise for petroleum resources. However, the study area’s hydrocarbon accumulation
process and mechanism are uncertain, seriously restricting further petroleum resource assessment in the eastern Kuqa Depression. Therefore, it is vital to reconstruct the hydrocarbon generation and expulsion history and analyze the hydrocarbon accumulation mechanism to discuss hydrocarbon exploration potential in the Tugerming area.

Many studies have reported oil and gas reservoir-forming mechanisms in the Kuqa Depression, focusing on various aspects, including the source of organic matter, hydrocarbon charging period and corresponding time, and the mode of hydrocarbon accumulation. Several researchers have investigated the origin of hydrocarbon in the Kuqa Depression. A widely accepted conclusion is that natural gas is primally derived from coal measure source rocks developed in the Middle and Lower Jurassic. By contrast, the Triassic lacustrine mudstone significantly contributes to the crude oil generation in the depositional depression. Moreover, there are different viewpoints on the discussion of petroleum charging and the accumulation processes. Liang et al. proposed a two-stage charging and late gas accumulation model for the Kuqa Depression. The Triassic source rocks generated lots of oils during the period of the Jidike Formation, and the vitrinite reflectance of source rocks in the Huangshanjie Formation was greater than 1%. Nevertheless, the Jurassic source rocks were in the immature stage. Concurrently, many faults were formed in the depression. Therefore, the oils produced by Triassic organic matter was expelled along the unconformity or sandstone carrier beds with lateral migration, forming an early oil reservoir. The second stage was mainly charged by natural gas since the Kuqa Formation (5–0 Ma). Finally, the Jurassic source rocks were buried rapidly and reached the highly mature stage, influenced by tectonic evolution. Thus, the large-scale natural gas derived from Jurassic coal-bearing source rocks has migrated in two directions. On the one hand, it migrated into the trap along the vertical migration pathways and caused hydrocarbon accumulation. On the other hand, it continued the lateral movement, causing the adjustment and destruction of the paleo-oil reservoir. As a result, the condensate oil and gas reservoirs were ultimately formed. In contrast, Li et al. and Zhao et al. believed that there were three periods of oil and gas migration in the Kuqa Depression, corresponding to the early-middle Kangcun period (17–10 Ma), late Kangcun to early-middle Kuqa period (10–3 Ma), and late Kuqa to Xiuy period (3–1 Ma), respectively. The Kangcun Formation-early Kuqa Formation stage was a critical moment for the formation of the oil reservoir sourced from coal-type organic matter. Moreover, the late Kuqa to Xiuy period was the major one for forming natural gas fields of high maturity to over-maturity. The early oil and condensate accumulation in the foreland thrust belts have been adjusted and even destroyed by the later intense orogenic events and the intrusion of natural gas.

In this paper, three geochemical techniques was used to comprehensively analyze the hydrocarbon accumulation and the mechanism in the Lower Jurassic reservoir of the Tugerming area, especially gas chromatography–mass spectrometry (GC–MS), comprehensive two-dimensional GC-time-of-flight MS (GC × GC–TOFMS), the observations of petrography and microthermometry characteristics of fluid inclusions and quantitative fluorescence technique (QFT). The biomarkers or biomarker parameters detected in the GC–MS technique covered a record of the origin and depositional environment of crude oils, showing the contribution of different types of organic matter. It was worth noting that the fluid inclusions documented lots of geological information, which was significantly useful for the understanding of the hydrocarbon expulsion and the charging time. The fluid inclusions in the reservoir were observed from the aspects of fluorescence development characteristics and the distribution of homogenization temper-

Figure 1. (A) Geographic location of the Tarim Basin in western China; (B) location map showing the tectonic units of the Tarim Basin and the Kuqa Depression adjacent to the South Tianshan Mountains; (C) location of the Well Tudong 2 in the Tugerming area of the eastern of Kuqa Depression (modified from ref 13).
ature. Combined with the results of quantitative grain fluorescence (QGF) and QGF on extract (QGF-E) experiments, the development of the paleo-oil reservoir and present oil reservoir in the Yangxia Formation were identified. By using the basin simulation software (Petromod), the hydrocarbon accumulation process was then modeled based on a set of burial history and thermal evolution history of source rocks in Well Tudong 2. This study not only played an important role in the systematical studies on the oil and gas charging and accumulation process of the Yangxia Formation in the Tugerming area but also provided theoretical guidance for further exploration and development in the eastern Kuqa Depression.

2. GEOLOGICAL SETTING

The Kuqa Depression is a foreland basin located in the southern part of the Tianshan orogenic belt. The depression, about 550 km (east to west) and 30–80 km (south to north), is surrounded by the North Tarim Uplift to the south.14 Multistage tectonic movements have happened in the depression since the Mesozoic. Furthermore, during the periods of Jurassic and Triassic strata deposition, the Indosinian and Early Yanshan movements occurred in sequence. As a result, they consisted of six tectonic units in the depression, corresponding to the northern monocline belt, the Klaus-Yiqiklik structural belts, the Baicheng-Yanxia sags, the Quilitag thrust belt, the southern gentle slope, and the Wushi sag, respectively.15 Our study target, the Tugerming area, is developed in the eastern Kuqa Depression. There are one faulted anticline and two faults developed in the study area, and the former is related to the Paleozoic uplift and the latter includes the Tugerming fault and Tuziluoke fault with fewer gypsum layers.16 Moreover, the Well Tudong 2 is located in the flanks of an anticline. Its Jurassic strata stopped drilling at a depth of 4400 m due to the weak display of oil and gas in the Lower Yangxia Formation. Therefore, there are mainly developed Cenozoic and Mesozoic sediment deposits in the depression according to the previous studies.16,17 The Cenozoic and Mesozoic strata comprise clastic strata such as mudstone, sandstone, coal interlayers, gypsum-salt, and conglomerate.18

Potential source rocks are developed in the Jurassic and Triassic strata. The Jurassic source rocks develop the local area with a thickness of 300–700 m, which is less thick than that of Triassic in the range of 200–600 m.2 Furthermore, the total organic contents (TOCs) have a significant difference. The TOC values of Jurassic source rocks range from 0.4 to 37.36%, whereas the values vary between 0.4 and 10.1% in the Triassic.2 The Mesozoic source rocks have been primarily in the mature-highly mature stage since the Late Tertiary. Mesozoic source rocks primarily generate condensate oil and gas at present, significantly contributed to the form of the condensate gas reservoir. There are six sets of petroleum source rocks in the Mesozoic strata (Figure 2), including Middle and Upper Triassic Kelamayi (T2k) Formations, Huangshanjie (T3h) Formations, Upper Triassic Taliqike (T3t) Formations, Lower Jurassic Yangxia (J1y) Formation, Middle Jurassic Kezilenuer (J2kz), and Middle Jurassic Qiakemake (J2q) Formations. The source rocks are formed in three depositional cycles.6 The Triassic organic matters are all formed in the first depositional cycle. At that time, the structural style shifted from a deep and steep faulted or gentle overlapping to a new style depression featured by the structurally stable and topographically flat,
causing the environmental transition from a shallow-semi-deep-deep lake to transitional swamp-lacustrine settings. The second depositional cycle controls the development of the source rocks in the Jurassic Yangxia Formation and Kezilenuer Formation. The sediments are deposited in alternate deltaic-swamp and lacustrine settings because of the intensive to weak transitional structural evolution. They not only developed a set of limnetic facies carbonaceous mudstone with a thickness of 200–400 m but also formed a 48.6 m thick coal seam.19 The Qiakemake Formation served as the primary source rocks in response to the structural style shifted from a rift to depression, and the climate changes from warm and humid to hot and dry. Controlled by tectonic evolution and depositional environment, the lacustrine source rocks are developed in the Kelamayi, Huangshajie, and Qiakemake Formations, but the coal measure strata are concentrated on the Taliqike, Yangxia, and Kezilenuer Formations.20

The Jurassic reservoir is distributed in the Yangxia Formation (J1y) and Ahe Formation (J1a), which is characterized by low permeability influenced by deep-buried and strong compaction1,21,22 (Figure 2). The coal measure source rocks interbedded with tight sandstone that cause the phenomenon that generated oil and gas migrated into the adjacent sandstone reservoir driven by source-reservoir pressure.23 There is an extensive accommodation space for gypsum-salt and lacustrine rocks with a moderate thickness.24 In addition, intense tectonic movements in the late period form effective hydrocarbon migration pathways and produce a hydrocarbon expulsion force.25 In all, the reservoir-cap rock assemblage of the Jurassic Kizilenuer Formation and Yangxia Formation is regarded as an efficient hydrocarbon accumulation combination, and shorter migration distances provide favorable geological conditions for the formation of large oil and gas reservoirs.

Table 1. Depth and Lithology of the Selected Samples

| samples | depth/m | lithology          |
|---------|---------|--------------------|
| TD2-1   | 3966    | pebbly coarse sandstone |
| TD2-2   | 3978.3  |                     |
| TD2-3   | 3978.8  |                     |
| TD2-4   | 3979.3  |                     |
| TD2-5   | 3980    | conglomerate        |
| TD2-6   | 3981.9  | sandstone           |
| TD2-7   | 3982.8  | pebbly coarse sandstone |
| TD2-8   | 3984    |                     |
| TD2-9   | 3984.5  |                     |
| TD2-10  | 3985.1  | pebbly fine sandstone |
| TD2-11  | 3985.4  | pebbly sandstone    |
| TD2-12  | 4135.4  | glutenite           |
| TD2-13  | 4136.7  | fine pebbly sandstone |
| TD2-14  | 4137.1  | pebbly coarse sandstone |
| TD2-15  | 4137.9  | pebbly sandstone    |
| TD2-16  | 4138.8  | fine sandstone      |
| TD2-17  | 4139.6  | pebbly coarse sandstone |
| TD2-18  | 4140.5  | glutenite           |
| TD2-19  | 4141    |                     |
| TD2-20  | 4142.2  | fine sandstone      |

The experiment was performed with a Thermo DSQ II instrument. The conditions for gas chromatography were as follows. The high purity helium (99.99%) was used as a carrier gas at a 1 mL/min constant flow rate. The chromatographic column was a HP-5 MS quartz flexible capillary column (60 m × 0.25 mm × 0.25 μm). The oven temperature was programmed from 60 to 260 °C at a rate of 6 °C/min and then increased slowly to 320 °C at 1.5 °C/min (held for 20 min). The ionization energy was set at 70 eV for mass spectrum analysis.

3.2. Fluid Inclusion Analysis. Fluid inclusions were detected using a Zeiss Imager A1M multifunctional microscope to identify the characteristics of petrography and microthermometry. Their petrography properties referring to the occurrence and fluorescence color and the phase state were determined using UV–visible and transmission light sources. The hydrocarbon inclusions and brine inclusions in different groups were selected, and their homogenization temperatures (T_h) were measured by a Linkam MDS-600 heating/cooling period was 10 s with a 2.5 shot jet timing. The transfer line temperature was 300 °C, which was 60 °C higher than that of the ion source. The detector voltage was set at 1600 V. Through a 9 min solvent delay, 100 scans/s were collected with the mass range of 40–500 amu.

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instrument under a normal pressure and temperature and humidity state.

3.2.4. QFT analysis (QGF and QGF-E Techniques). First, approximately 2 g of ground quartz grains with a size of 0.063–1.000 mm were put into a 50 mL beaker mixed with 20 mL of high-performance liquid chromatography (HPLC) grade dichloromethane (DCM). Then, a beaker was put into an ultrasonic oscillator to bathe for 10 min, followed by drying the grains at room temperature. Second, the dry grains mixed with 40 mL of 10% H₂O₂ were prepared by subjecting them to ultrasonic vibrations twice and each time it was continued for 10 min with a rest for 40 min in the fume hood. Then, 40 mL of 3.6% HCl was put into the breaker to undergo ultrasonic vibration for 10 min. When no bubbles appeared in the beaker, the grains were washed several times with distilled water and dried in an 80 °C constant temperature drying oven for about 1–4 h. Finally, the remaining grains were re-washed in 20 mL of HPLC grade DCM in an ultrasound bath for 10 min, and then the solvent was preserved for QGF-E analysis. Meanwhile, the separated grains were dried at room temperature for QGF analysis.

The experiments were all conducted in the Key Laboratory of Basin Structure and Hydrocarbon Accumulation in the Research Institute of Petroleum Exploration and Development of China.

4. RESULTS

4.1. Physical Property and Maturity of Oil. Tarim Oilfield Company, PetroChina, provides the data of physical property analysis for the condensate oil samples. The density is generally low, ranging from 0.81 to 0.82 g/cm³ at 20 °C. The oil viscosity ranges from 0.91 to 2.37 mPa·s at 50 °C, with an average of 1.31 mPa·s (n = 5). The content of wax is in a range of 3.80–10.50% of the total contents. The oil is seen as a low sulfur type because its sulfur abundance is less than 0.1%. There is a small percentage composition of resin and asphaltene, both less than 1%. The freezing point does not exceed 5 °C. In all, massive condensate oils gathered in the reservoir of Lower Jurassic in Well Tudong 2 are characterized by low density, low viscosity, and trace sulfur. In addition, the carbon isotope of the crude oil is −23.5‰ tested by Tarim Oilfield Company, PetroChina, which is of a similar feature to the coal-derived oils in the Kuqa Depression.

A comprehensive two-dimensional GC × GC−TOFMS technique has recently been used to make a detailed composition of crude maturity based on the abundances of diamondoid compounds. Diamondoid series have the remarkable characteristics of a small molecular weight and single structure. Its chemical properties are highly stable and generally not affected by external factors due to the solid resistance for thermal degradation and biodegradation, especially in hydro-
carbon generation and evolution of organic matter.\textsuperscript{29,30} Therefore, the technique had a wide range of applicability.\textsuperscript{31} Previous studies have found that it is an indicator for determining the condensate oil maturity in Tarim Basin.\textsuperscript{32} There are multiple substituent positions in the structure of diamondoids, and different positions represent respective thermal stability. With maturity increasing, the isomers with strong thermal stability become dominant. Considering that the 1-methyladamantane (1-MA) is more stable than 2-methyladamantane (2-MA), their relative contents are used as an evaluation parameter for crude oil maturity.\textsuperscript{33,34} The diamantane compounds continually appeared in the geological body with organic matter maturity greater than 1.0%. Meanwhile, the thermal stability of 4-methyl adamantane (4-MD) is the best, followed by 1-methyl adamantane (1-MD) and 3-methyl adamantane (3-MD) are the worst.\textsuperscript{35} Thus, Chen et al.\textsuperscript{33} not only established the methyl methyl adamantane index (MAI) according to the relative contents of the 1-methyl adamantane and 2-methyl adamantane (MAI = 1-MA/(1-MA + 2-MA)) but also created the methyl methyl adamantane index (MDI) based on the relative abundances of isomers of methyl adamantane (MDI = 4-MD/(1-MD + 3-MD + 4-MD)). The results showed that the content of the 1-methyl adamantane compound was 1298.01 ppm, the 2-methyl adamantane was 511.89 ppm; thus, the calculated MAI was 50−70% (Figure 3A). Furthermore, the content of 4-methyl adamantane was 13.98 ppm, 1-methyl adamantane was 11.23 ppm, and 3-methyl adamantane was 10.41 ppm, and then measured MDI was 30−40% (Figure 3B). The results suggested that the vitrinite reflectance of detected condensate oil was in the region of 1.1−1.3% (Table 2), which was regarded as the product of the source rocks in the maturity stage.

### Table 2. Relation between MAI and MDI Values and Vitrinite Reflectance (Based on ref 36)

| MAI/% | MDI/% | Ro/% |
|-------|-------|------|
| 50−70 | 30−40 | 1.1−1.3 |
| 70−80 | 40−50 | 1.3−1.6 |
| 80−90 | 50−60 | 1.6−1.9 |
| >90   | >60   | >1.9 |

The natural gas in the study region was typical wet gas. The methane took an absolute dominance of the natural gas components with the highest content of 82.91%. By comparison, ethane showed a small abundance with a value of 7.27%. The components with the highest content of 82.91%. By comparison, methane took an absolute dominance of the natural gas stage. The carbon isotope content of ethane in natural gas was 25.5‰. It was measured as 0.88 based on the abundance of the C19 to C24 compounds were detected, and they showed a normal distribution. However, there was a significant variation in the C19 TT compounds, in which the C19 TT compound was predominant. On the other hand, the contents of gammacerane and C29 Ts compounds were in weak display. The regular C29 sterane (C29st), acting as irregular C29 sterane (C29snt), and C29 sterane (C29ph). Considering the biomarker distributions, they were classified into four types in the detected samples.

(A) Taking the coarse sandstone sample at 3979.3 m as the representation (Figure 4A), the distribution of TT displayed a step-like decreasing pattern for C19 TT in the m/z 191 mass chromatogram, which showed the following order of abundance: C19 TT > C20 TT > C21 TT > C22 TT > C23 TT. The content of the C19 TT compound took the most significant proportion in the TT. Moreover, the relative abundance of Tm increased than that of Ts. The diaC30 H was in abundance than the C29Ts compound. On the other hand, there was only a tiny amount of gammacerane compound. Besides, the significant predominance of the regular C29 sterane was notable in the m/z 217 mass chromatogram, and the content of regular C29 sterane was the lowest, forming inverse “L” of the distribution of C27st, C28st, and C29ph.

(B) Little samples showed different biomarker distributions from A-type, such as the coarse sandstone sample at 3982.8 m (Figure 4B). The TT from C19 to C24 compounds were all detected, and they showed a normal distribution, which meant the abundance order of TT was as follows: C19 TT < C20 TT < C21 TT < C22 TT > C23 TT. Abundance in C23 TT or C24 TT was displayed in the m/z 191 mass chromatogram. There was only a slight variation between the Ts compound and Tm compound compared to the A category. Moreover, the gammacerane, diaC30 H, and C29 Ts compounds were in weak display. The regular C29 − C29 steranes showed “L”, with the most abundant of C29st.

(C) The results of the mass chromatograms of the glutinites sample at 4135.4 m are shown in Figure 4C. The distribution of TT was similar to A-type, showing a step-like distribution. However, there was a significant variation in the C19 TT-C24 TT compounds, in which the C19 TT compound was predominant. On the other hand, the contents of gammacerane and C29 Ts were similar to the B category. Moreover, the diaC30 H was abundant. Interestingly, it showed a new distribution pattern of regular C27 − C29 steranes, acting as irregular “V.” Moreover, the content of C29 ph was slightly enriched than the C29st.
There were some notable observations in the mass chromatograms of the pebbly sandstone at 4137.9 m (Figure 4D). It was observed that the C₁₉−C₂₄TT displayed a step-like distribution. Moreover, the C₁₉TT was the highest in content. Regular C₂₇−C₂₉ steranes were all detected with the distribution of irregular “V.” In comparison to the regular steranes in the C category, the C₂₉st compound was predominant compared to the C₂₇st. Moreover, the contents of Tm and Ts compounds increased generally. The diaC₃₀H was more abundant than the C₂₉Ts compound.

4.3. Petrography and Microthermometry Characteristics of Fluid Inclusions. When hydrocarbons expelled from source rocks migrated into the reservoir, they were captured by mineral grains with the formation fluid, forming multiple charging episodes of hydrocarbon inclusions and aqueous inclusions. Therefore, it was crucial for investigating the petrography and microthermometry of inclusions to categorize the different inclusion groups in the reservoir. The petrography characteristics included the fluorescence colors, shapes, dimensions, and existing positions under transmitted light (TR) and ultraviolet light (UV), and microthermometry was to heat the inclusions into a single liquid to show their homogenization temperatures (Tₜ).
The clastic samples under the multifunctional microscope found numerous oil inclusions with different fluorescent colors. By integrating the observational information, the investigative fluid inclusion assemblies were divided into three types in the Yangxia Formation reservoir of Well Tudong 2.

(i) Yellow fluorescing oil inclusions and coexisting aqueous inclusions displayed diameters of approximately 5–10 μm, and the GOI of hydrocarbon inclusions ranged from 5 to 8%. They were generally hosted within the cracks of quartz grains with an elliptical or irregular shape. These kinds of inclusions were typically in pure liquid phases (Figure 5B,C), and another type of vapor–liquid (V–L) two phase was also present with a small volume of the bubble (Figure 5D), though limited in number at room temperature. The observational hydrocarbon inclusions were featured as a group (Figure 5B), beaded (Figure 5C), or sporadic distributions (Figure 5D) in the fracture of quartz grains. It was worth mentioning that there was an individual bubble shown in Figure 5D. Moreover, the bubble present in the petroleum inclusion was black under ultraviolet illumination, and the hydrocarbon around it presented yellow fluorescence. The oil inclusions contained a high proportion of heavy components, this being the result of yellow fluorescence.

The petroleum inclusions in this category had a normal homogenization temperature distribution between 115 and 145 °C. Moreover, the values of coexisting aqueous inclusions mainly ranged from 125 to 135 °C.
(ii) A group of oil inclusions showed blue-white fluorescence and was surrounded by massive aqueous inclusions. Likewise, their diameter varied from 5 to 10 μm, whereas the GOI value was 8–10% greater than the yellow oil inclusions. The hydrocarbon inclusions transected the adjacent quartz grains (Figure 5E) and occurred in the individual quartz grain (Figure 5F), in which they were in the linear distributions. In addition, it was found that the blue-white hydrocarbon inclusions were observed in a pure liquid phase (Figure 5E,F) or gas–liquid two-phase in some cases (Figure 5G). The color of the bubble varied from colorless under TR to black under UV in Figure 5G. Interestingly, the petroleum inclusions in this category were cross-cutting the yellows, responding to different charging stages. There were two nearly parallel blue-white inclusions intersected with linearly distributed yellow inclusions (Figure 5H). The cross-cutting relationship in Figure 5I presented that the blue-white inclusions divided the linear yellow inclusions into two parts, supporting the conclusion that the charging time of blue-white inclusions was later than that of yellow inclusions. The blue-white fluorescence of oil inclusions implied that the oil was composed of lightweight components. The Tn values of blue-white fluorescent oil inclusions were in the range of 125–150 °C. The corresponding coexisting aqueous inclusions had the Tn from 135 to 150 °C.

(iii) Gas inclusions and solid–liquid two-phase inclusions were formed by gas charging. It was seen that there was a black ellipse inside an inclusion under TR (Figure 5J), which also showed a black ellipse in the yellow fluorescent inclusion under UV (K). The shape of the inclusion was well preserved, and there was no apparent leakage. The solid material was dissolved in liquid hydrocarbon when heated, suggesting that the black item was bitumen caused by gas washing. In addition, numerous residual bitumen was discovered in the intergranular pores (Figure 5L). Unfortunately, the homogenization temperatures of gas inclusions were difficult to measure due to their minimal size. Nevertheless, the Tn results of their coexisting aqueous inclusions were greater than 150 °C.

4.4. Development of Ancient and Present Oil Reservoirs. We collected a total of 20 sandstone samples from the Yangxia reservoir to analyze QGF and QGF-E. QGF reflected the fluorescence characteristics of oil inclusions in particles and residual hydrocarbons adsorbed on the surface of the particles, whereas QGF-E characterized the fluorescence properties of the hydrocarbon extraction solution adsorbed on the surface of the reservoir particles. Both techniques were rapid, efficient, and convenient for nondestructive analysis. Therefore, they were widely used in the petroleum reservoir evaluation. The systemic techniques were developed to detect paleo-oil-water contacts (POWCs), and current OWC in petroleum wells. The characteristic fluorescence parameters referring to the QGF index and QGF-E intensity were obtained from the experiment results. The QGF index was defined as the average spectral intensity between 375 and 475 nm normalized to the spectral intensity at 300 nm and responded to paleo-oil saturation. QGF intensities were the maximum spectral intensity of a QGF-E spectrum normalized to weight and volume and responded to the current hydrocarbon saturation. In general, the QGF index values exceeded 4 in the paleo-oil zone.

Furthermore, the current or residual hydrocarbon zone presented the values of QGF-E intensity as greater than 40 pc, and almost all water zone had values of less than 20 pc. The spectral parameter of Lambda-Max (λmax) appeared in the QGF fluorescence spectra and presented in the QGF-E fluorescence spectra, which represented the wavelength in nm of the maximum spectral intensity. The experimental results have made qualitative and quantitative analyses on the development of the oil reservoir in the Yangxia Formation of Well Tudong 2. The distribution of the QGF index values was concentrated from 3.8 to 12.7 in the depth of 3966–4142.2 m (Table 3). The maximum QGF index value was 12.7 at 3978.3 and 3978.8 m, and the other values at different depths were less than 10. The deepest in the studied interval had the minimum QGF index value (3.8), less than 4. All samples above 4142.2 m had values more than 4 with no particular trend. It was, therefore, possible to identify the paleo-oil-water contact at around 4142 m. The QGF intensities displayed no particular variation between 1.2 and 4 (Figure 6A), and λmax values shifted from 390 to 490 nm. Compared to QGF fluorescence spectra, there was only one peak in the QGF-E fluorescence spectra and λmax was around 370 nm (Figure 6B), similar to the feature of light oil. The

### Table 3. Fluorescence Parameters in the QGF and QGF-E Techniques

| Sample | QGF | QGF-E |
|--------|-----|-------|
|        | index | intensity/pc | λmax | intensity/pc | λmax |
| TD2-1  | 5.9  | 1.3          | 398.7 | 12.8          | 370.0 |
| TD2-2  | 12.7 | 3.9          | 484.5 | 1560.7        | 371.0 |
| TD2-3  | 12.7 | 3.6          | 485.0 | 2349.6        | 373.0 |
| TD2-4  | 7.4  | 2.1          | 486.4 | 911.2         | 373.0 |
| TD2-5  | 6.5  | 2.0          | 426.2 | 2063.5        | 371.0 |
| TD2-6  | 5.9  | 1.4          | 397.8 | 782.0         | 370.0 |
| TD2-7  | 7.7  | 1.8          | 432.8 | 1764.1        | 369.0 |
| TD2-8  | 8.2  | 1.7          | 442.2 | 1593.8        | 370.0 |
| TD2-9  | 8.2  | 1.7          | 430.7 | 949.9         | 367.0 |
| TD2-10 | 5.4  | 1.7          | 406.2 | 566.5         | 370.0 |
| TD2-11 | 7.2  | 1.7          | 420.4 | 504.4         | 367.0 |
| TD2-12 | 7.3  | 3.4          | 441.6 | 296.8         | 371.0 |
| TD2-13 | 4.0  | 1.2          | 394.6 | 137.8         | 369.0 |
| TD2-14 | 5.0  | 1.6          | 396.6 | 146.0         | 368.0 |
| TD2-15 | 4.5  | 2.0          | 402.5 | 163.2         | 370.0 |
| TD2-16 | 5.0  | 2.0          | 410.1 | 128.9         | 366.0 |
| TD2-17 | 6.3  | 1.9          | 408.7 | 93.8          | 366.0 |
| TD2-18 | 5.4  | 2.2          | 411.9 | 228.0         | 371.0 |
| TD2-19 | 4.8  | 1.6          | 399.5 | 100.8         | 371.0 |
| TD2-20 | 3.8  | 1.7          | 398.6 | 85.0          | 369.0 |
evidence also suggested that there was once a paleo-oil reservoir in the Yangxia Formation, but it was seriously damaged by the gas charging and tectonic action in the late period.

5. DISCUSSION

5.1. Origin and Depositional Environment of Oil. Some stable compositions in the dead organism gradually transformed into biomarkers that maintained the original biochemical constituents’ skeleton structure. Therefore, the biomarker compounds could provide geological information on the source and depositional environment of organic matter and crude oil. Notably, there was some inaccuracy in evaluating the origin of crude oils in the highly mature stage of source rocks. The vitrinite reflectance of the condensate oil in the study region was about 1.0%, being in the mature stage, and thus the biomarker parameters could be practical to distinguish different types of organic matters. Understanding biomarkers’ contents and geochemical characteristics were two significant aspects of determining the source rocks and depositional environment. The TT and steranes were essential components in the saturated hydrocarbon and played vital roles in the petroleum geochemical evaluation. Generally, the TT series compounds with carbon numbers less than 21 were derived from higher plants. The distribution of TTs in coal-derived oils in the Kuqa Depression was dominated by low carbon numbers with a prominent peak of C19TT. Regular steranes were also important evaluation indicators to identify the biogenic composition of organic matter. It was generally believed that regular C27 and C28 steranes originated from aquatic organisms, whereas regular C29 sterane was often related to higher plants.

Most TTs in the m/z 191 mass chromatogram of the investigative samples showed step-like distributions, and the contents of low carbon numbers of TTs had an absolute advantage, with C19TT as the prominent peak. In addition, some specific biomarker parameters were quantitatively analyzed. The C19−21TT/C23−24TT parameter values ranged from 1.04 to 4.86, with an average value of 2.90 (Table 4). Then, the relative abundances of C19+20TT, C21TT, and C23TT were set as the three elements to construct a ternary diagram (Figure 7A). It was found that most sample points had an intensive distribution in the lower-left region, where the sum contents of C19TT and C20TT were distributed in 50−72%, and the relative abundance...
of C_{21}TT was less than 28%. In addition, the relative content of regular C_{29} sterane had a dominant abundance (Figure 7B), and it showed an inverse L-type or irregular V-type of the distributions of C_{27}st, C_{28}st, and C_{29}st in the m/z 217 mass chromatogram.

Moreover, we measured the relative percentage contents of regular steranes. Figure 7B shows that C_{27}st had the lowest contents on the whole, with a minimum value of 16.97%. Besides, except for the maximum value (46.92%), other values were less than 30%. The C_{28}st was modestly abundant (25−40%) (Table 4), and the maximum value was 39.28%. The relative content of C_{29}st occupied a large proportion, fluctuating between 26.96 and 51.78%, and most of them ranged in 40−50%. The relative content of C_{29}st occupied a large proportion, fluctuating between 26.96 and 51.78%, and most of them ranged in 40−50%. The relative content of C_{29}st was generally higher than that of C_{27}st, but the C_{27}st was seen as the highest content compound in sample TD2-7, corresponding to a high content of TTs with high carbon numbers. In addition, the scatter plot of parameter values C_{19−21}TT/C_{23−24}TT and C_{27}st/C_{29}st was drawn (Figure 7C), and it showed that most sample points were relatively concentrated. The range of parameter values of C_{19−21}TT/C_{23−24}TT was between 1.5 and 5.0, and C_{27}st/C_{29}st was less than 0.8. The parameter data with mass chromatogram characteristics indicated that crude oils extracted from the target reservoir had different sources, which were predominated by terrestrial higher plants.

The compounds of gammacerane, C_{29}Ts, and diaC_{30}H compounds were generally related to the oxidation−reduction nature of depositional environments. It was widely believed that a depositional environment with high salinity and strong reduction was favorable for the formation of gammacerane but was adverse for rearranged hopane compounds, which were gathered in the freshwater water environment with partial oxidation.44

A Ts/(Ts + Tm) value was between 0.29 and 0.51, with an average of 0.38 (Table 4). Only the parameter value of the TD2-12 sample was 0.51, greater than 0.5, and other parameter values were all less than 0.5, which provided the cognition that the content of Ts was relatively low. The ratio of diaC_{30}H/C_{29}Ts was 0.66−4.50, with a mean value of 3.28. Only the parameter value of the TD-7 sample was 0.66, and the other values were generally greater than 2, indicating a freshwater depositional environment. Except for the TD2-7 sample, the results of other
samples were all greater than 1, indicating that diaC30H was relatively in abundance. It could be seen that the gammacerane compound was trace with the imprecise calculation of its content (Figure 4). In addition, the relative contents of TTs were also used to indicate depositional environments. Xiao et al.\(^46\) have established a depositional environment identification plate with the relative abundance of C\(_{19}\)TT−C\(_{23}\)TT, which could distinguish marine/saltwater lacustrine facies, freshwater lacustrine facies, and river/delta and swamp facies. The samples were put into the identification plate, and it was found that the sample points were mainly distributed in the swamp facies source rock or crude oil region.

In all, the crude oil from Yangxia Formation in Well Tudong 2 was mainly derived from terrestrially higher plants mixed with some lower aquatic organisms, deposited in the freshwater depositional environment of swamp facies, which was consistent with biomarker characteristics of coal measure source rocks of the Jurassic Yangxia Formation in the Kuqa Depression.\(^{47}\)

The carbon isotope content of ethane was −25.5‰ in the natural gas from Well Tudong 2 according to Tarim Oil field, a typical coal-type gas. Circumstantial evidence was presented to show the importance of middle-lower Jurassic coal measures as gas source rocks in the Kuqa Depression.\(^{20}\) Considering that the coal measure source rocks in the Jurassic were widely developed than that in the Triassic, which only contained a thickness of less than 10 m,\(^{18}\) it suggested that the Jurassic source rocks serve as a primary source for hydrocarbon generation for the current gas reservoir.

5.2. Time and Stages for Petroleum Charging. The charging history of oil and gas was a vital problem for determining the formation and distribution of the hydrocarbon reservoir in the basins. In recent years, the experiments of the hydrocarbon charging process had improved from qualitative research to detailed semi-quantitative and quantitative analyses, and a mass of new analytical techniques have appeared. Several studies demonstrated the significance of fluid inclusions in understanding the petroleum migration histories in depositional basins.\(^{49}\) Fluid inclusions were direct historical records, which contained fluid temperatures, pressures, and compositions during hydrocarbon charging.\(^{50}\) The detection of fluid inclusions provided powerful evidence for the determination of hydrocarbon charging time and periods.\(^{50}\) It was noteworthy that the fluorescence color of oil inclusions was related to oil mature and composition. As oil maturity increased, the inclusion fluorescence gradually turned from brown to blue-white. Generally, the inclusions were formed in the homogenization condition when hydrocarbon was charged into the reservoir. Therefore, the current hydrocarbon inclusions in the reservoir needed to be heated to recover the homogenization state, and the corresponding temperature served as the homogenization temperatures of inclusions. Combining the homogenization temperatures of different fluid inclusions with burial histories could determine the charging time of oil and gas in each period.\(^{50}\)

The early studies on the tectonic evolution history of the Tugerming area were of great importance for reconstructing the burial history of Tudong 2. The present thickness and denudation thickness of each stratum and ages of deposition and denudation were obtained from previous research.\(^{26}\) Additionally, we took 20.0 °C as the paleo-surface temperature. The geothermal gradient of the Mesozoic was set at 3.1 °C/100 m and then decreased from 2.8 °C/100 m to 2.5 °C/100 m since Paleogene.\(^{51}\) Finally, we used basin simulation Petromod software to reconstruct the burial history of Well Tudong 2 by combining the above geological parameters with heat-flow values\(^{52}\) in the Kuqa Depression (Figure 8). It should be noted that the depths of the Ahe Formation and Triassic strata were simulative because the target well was only drilled to the Yangxia Formation.
Formation until 4400 m. The burial history was characterized by “long-term shallow burial in the early and subsequent rapid, deep burial, and tectonic uplift in the late,” the corresponding temperature curves turned from sparse to dense.

We chose the homogenization temperatures of coexisting aqueous inclusions in different inclusion groups as the charging temperatures because they were more accurate than that of hydrocarbon inclusions. The homogenization temperature of
aqueous inclusions in the first stage was in a range of 125–135 °C, corresponding to 15–10 Ma based on the burial history. The temperature of the Yangxia Formation in the period of 9–6 Ma was consistent with the homogenization temperature of the aqueous inclusions in the second stage, which ranged from 136 to 150 °C; this was to say, the second oil charging stage was from 9 to 6 Ma. The homogenization temperature of the aqueous inclusions associated with natural gas in the third stage exceeded 150 °C, suggesting that the natural gas migration and accumulation occurred since 5 Ma.

QGF and QGF-E experiments showed the development of paleo-oil zones and residual or current oil zones in the Yangxia Formation of Well Tudong 2. The QGF index values were relatively concentrated and almost exceeded 4, proving the paleo-oil reservoir once existed corresponding to the first type of fluid inclusions. Only the QGF index at the bottom was less than 4, and the other depths were greater than 4, indicating that the paleo-oil-water contact was distributed at about 4142.2 m (Figure 9). The λ_{max} exceeded 400 nm in QGF fluorescence spectra, consistent with the discovery of yellow fluorescent oil inclusions, implying the paleo oil was dominated by high components. Likewise, the QGF-E fluorescence spectra displayed the unimodal characteristics accompanied with the λ_{max} values concentrated at 400 nm, suggesting that light components had a significant proportion in current oil. This was associated with the discovery of numerous blue-white fluorescent oil inclusions in the samples. Besides, the QGF-E intensity was remarkably greater than 4. Meanwhile, the evidence of fluorescence characteristics also proved that the early reservoir of Well Tudong 2 was seriously damaged by late gas washing, causing the current reservoir to mainly accumulated light oil and natural gas.

5.3. Thermal Evolution of Jurassic Source Rocks.

Similar to the process of burial history reconstruction, we used basin simulation software PetroMod to simulate the hydrocarbon generation process and reconstruct the thermal evolution of Jurassic source rocks of the study well, based on the model provided by Burnham and Sweeney. It was a meaningful discussion on the time matching relationship between hydrocarbon charging and hydrocarbon generation in the geological assessment. The structural evolution in the depositional basins significantly controlled the maturity of source rocks. The nappe structure was predominantly developed since Miocene, resulting in forwarding thrust structures and various fault-related folds. The tectonic movement was intense in the late period, and the tectonic compression intensity reached the highest in the late Himalayan period, which played a dominant role in the process of the hydrocarbon reservoir formation in the eastern Kuqa Depression.54

Triassic and Jurassic source rocks in the study area had long-term shallow burying and short-term deep burying, controlled by tectonic evolution.55 The Mesozoic source rocks were buried in the shallow area with low thermal maturity in the initial phase, and then the stratum entered the rapid deposition process since the late Pliocene. In this paper, the values of vitrinite reflectance (Ro %) of source rocks during different hydrocarbon charging stages are the focus of this discussion. The modeled results (Figure 10) showed that the Ro of source rocks at the top of the Yangxia Formation reached 0.6% at 15 Ma, and the mature at the base of Yangxia Formation was about 0.72%. If a vitrinite reflectance of 0.6% was seen as the threshold for oil generation, the source rocks of Yangxia Formation in the early mature stage just started to produce oil in the first period of hydrocarbon charging. The maturity of Jurassic source rocks was in the range of 0.7–0.8% at 10 Ma. Thus, the source rocks in the Yangxia Formation were in the stage of early-middle maturity (0.6–0.8 Ro %) during the first period of crude oil charging (15–10 Ma), interpreting the phenomenon of early hydrocarbon inclusions displaying yellow fluorescence and the higher value of λ_{max} in the QGF fluorescence spectra. However, there were apparent differences in the thermal evolution of Jurassic and Triassic organic matters. The maturity of Triassic source rocks was higher than that in the Jurassic, and Triassic organic matter has already entered the maturity stage in the same time interval, generating a small amount of lacustrine oil. As seen from Figure 10, during the second crude oil charging period (9–6 Ma), the source rocks in the Yangxia Formation quickly reached the middle-maturity stage, and the values of Ro were in a range of 0.75–1.0%.

Moreover, it was a condensate generation peak for the coal measure source rocks of the Yangxia Formation. Concurrently, blue-white fluorescent hydrocarbon inclusions were captured in the reservoir, with the λ_{max} around 370 nm in the QGF-E fluorescence spectra. Moreover, the maturities of Jurassic source rocks were consistent with the maturity of condensate oil samples calculated by GC × GC–TOFMS. At this time, Triassic source rocks were in the high-over mature stage and produced wet gas and dry gas. However, since 5 Ma, the maturity of the source rocks in the Yangxia Formation was evident in the highly mature stage with the Ro value exceeding 1.05%, generating abundant condensate oil and wet gas. Therefore, it was proved that the thermal evolution of source rocks of the Jurassic Yangxia Formation had a great hydrocarbon generation potential, which was contrary to the previous conclusion that the Jurassic hydrocarbon was mainly derived from the Triassic source rocks.

5.4. Hydrocarbon Process in the Lower Jurassic Reservoir.

The Kuqa Depression has experienced three evolution phases: a foreland basin during the Late Permian to the Triassic, a continental depression during the Jurassic, and a rejuvenated foreland basin from the Cretaceous to Quaternary age.56 There were six main tectonic movements in the depression since Mesozoic, and they were the Indosinian movement, the Early Yanshan movement, the Late Yanshan movement, the Early Himalayan movement, the Middle Himalayan movement, and the Late Himalayan movement, respectively. Several thrust faults and accompanying fold structures formed in the Kuqa Depression during the Paleogene to Quaternary.58 The quantitatively seismic interpretations and balanced restorations to analyze the structural geometry and kinematics of the Tugerming structural belt were addressed by Chai et al.59 Thus, we analyzed the hydrocarbon accumulation process in the Lower Jurassic reservoir based on the tectonic evolution history described by Chai et al. Well Tudong 2 was located in the structural high point of the ancient anticline. The matching between tectonic activity and hydrocarbon generation and expulsion history determined the charging characteristics and accumulation process of Jurassic condensate oil and gas in the eastern Kuqa Depression. The Himalayan compression movement played an important role in reservoir formation in the depression, which not only formed migration pathways and trap structures for hydrocarbon accumulation but also was the predominant driving force for hydrocarbon migration.54

Based on the comprehensive analysis of tectonic evolution history, burial history, and thermal evolution history of source rocks, it was indicated that there was a model of hydrocarbon early charging and late accumulation in the Yangxia Formation.56
of Well Tudong 2. There were three hydrocarbon charging events in the study area (Figure 11), corresponding to mature oil charging in the early-middle stages of Miocene, highly mature condensate oil migration in the late Miocene and large-scale natural gas accumulation since Pliocene. First, the coal measure source rocks in Lower Jurassic just reached the threshold of oil generation and started to produce crude oil during the early-middle period (15−10 Ma) of the Kangcun Formation. Concurrently, the initial shape of low amplitude anticline was formed in the Tugerming area caused by tectonic compression, and thus the generated coal-derived oil was expelled laterally under extrusion stress into the reservoir. Simultaneously, a small amount of lacustrine oil generated from Triassic source rocks migrated upward to the reservoir along faults and was mixed with coal-derived oil to form the early reservoir. Hydrocarbon inclusions with yellow fluorescence in the reservoir recorded the oil charging process in the first stage, and the $\lambda_{\text{max}}$ in the QGF fluorescence spectra exceeded 400 nm. The residual bitumen (solid oil) in the yellow fluorescent oil inclusion demonstrated that the crude oil in the early period was adjusted by gas washing in the late stage. The buried depth of the Mesozoic stratum increased rapidly due to the aggravated tectonic compression in the time interval from the late Kangcun Formation to the early period of Kuqa formation (9−6 Ma), which led to a sharp increase in the maturity of Jurassic source rocks. A large amount of light crude oil was originated from the middle-mature coal measure source rocks and then charged into the reservoir with lateral migration, corresponding to the hydrocarbon inclusions with blue-white fluorescence. In addition, the stage was recorded by the characteristic fluorescence spectra of QGF-E. It was the mass gas generation stage from the Jurassic coal seam since the late stage of Kuqa Formation (5−0 Ma), corresponding to a period of intense activity of the Tugerming structural belt. The vital episode occurred when the strata were further folded, and the trap was gradually uplifted with increased capacity. The generated large-scale natural gas was expelled and accumulated in the high part of the structure under the gas expansion. Significantly, the early oil reservoir was adjusted in gas charging, resulting in the loss of $n$-alkanes and the enrichment of heavy components in the crude oil. In addition, the oil−gas leakage

Figure 11. Geological model of oil and gas migration and accumulation in the Yangxia reservoir of Well Tudong 2 in the Tugerming area. (A) Crude oil was expelled into the Yangxia reservoir during the first stage of 15−10 Ma; (B) massive condensate oil was charged into the Yangxia reservoir in the second period of 9−6 Ma; and (C) large-scale condensate gas accumulation occurred in the Yangxia reservoir since Kuqa Formation (5−0 Ma).
window was formed affected by intense tectonic activation in the late, which led to the severe destruction of the ancient oil reservoir.

Based on the analysis of structural evolution, hydrocarbon migration, and accumulation process, the hydrocarbon accumulation mechanism acted as self-generation and self-storage in the Lower Jurassic reservoir in the eastern Kuqa Depression. This accumulation mode had significant advantages of short migration distance, less loss, fast charging, and high efficiency, which was similar to the Dina 2 large condensate gas field. Therefore, our study suggested significant hydrocarbon generation potential in the Lower Jurassic reservoir of the eastern Kuqa Depression.

6. CONCLUSIONS

(1) The crude oil and natural gas from the Lower Jurassic reservoir in the eastern Kuqa Depression were mainly derived from the Jurassic coal measure source rocks and mixed with a small contribution of Triassic source rocks. Using the GC−MS technique on the saturated hydrocarbons extracted from clastic rocks in the Yangxia Formation of Well Tudong 2 was significantly helpful to identify the origin and depositional environment of crude oils. The characteristics of the detected biomarkers were as follows. The TTs in most samples showed a step-like distribution, with a prominent peak of C_{19}TT. Moreover, the low carbon numbers of TTs were dominant in the contents compared to the high carbon numbers. Moreover, the regular steranes primarly showed an inverse L-type or an irregular V-type, and the contents of regular C_{29} sterane were generally more than that of regular C_{27} sterane. The diaC_{19}H had a relatively higher abundance than C_{29}Ts, and the gammacerane was trace with a weak display. In addition, the Tm compound had a higher content than Ts. From the integrated characteristics of biomarker parameters, we found that the crude oils originated from higher plants deposited in the freshwater depositional environment, consistent with the characteristics of coal measure source rocks of the Jurassic Yangxia Formation. Furthermore, in consideration of regional high-quality Jurassic coal seam directly overlaying the Triassic source rocks, it is suggested that Jurassic source rocks dominated the natural gas.

(2) There are three periods of oil and gas charging in the Lower Jurassic reservoir of Well Tudong 2. First, the Jurassic coal measure source rocks reached the oil generation threshold in the early-middle Kangcun Formation (15−10 Ma). The generated mature oil was expelled into the reservoir, forming yellow fluorescent hydrocarbon inclusions. The QGF index was greater than 4 in the first stage of hydrocarbon charging, and the corresponding λ_{\text{max}} values were generally greater than 400 nm, suggesting that heavy components dominated the early oil. The maturity of Jurassic source rocks sharply increased during the second stage of 9−6 Ma and generated numerous condensate oil, which was charged into the reservoir. The blue-white fluorescent hydrocarbon inclusions captured in the reservoir recorded the second episode. The QGF-E fluorescence spectra were characterized by a unimodal form with a λ_{\text{max}} less than 370 nm. Furthermore, most of the QGF-E intensity values exceeded 40 pc, which was of a similar interval to paleo-oil zones. The natural gas captured in the current reservoir was the product of the highly mature Jurassic source rocks. Moreover, the gas migration and accumulation has occurred since the Kuqa Formation (5−0 Ma). The oil pools formed in the early stages have experienced intensive gas invasion and tectonic compression, resulting in the light components of oils being taken away and the reservoir being seriously destroyed.

(3) Both oil and gas were mainly derived from the Jurassic source rocks, but gas was charged into the reservoir later than oil. The accumulation mechanism had the characteristics of self-generation and self-storage, which was similar to the Dina 2 gas reservoir. The trap was formed in the late period, which was controlled by the Himalayan tectonic movements. There were some significant advantages in the hydrocarbon migration and accumulation, especially short migration distance, efficient hydrocarbon charging, and late accumulation, providing favorable geological conditions for forming large oil and gas reservoirs in the eastern Kuqa Depression.

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Notes
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