

Research Article

Differential Characteristics and the Main Controlling Factors of Shale Oil Sweet Spot Reservoirs in Lucaogou Formation, Jimsar Sag, Junggar Basin

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The microscopic differences in characteristics and formation mechanism of shale oil reservoirs in the upper and lower sweet spot sections of the Lucaogou Formation in the Jimsar Depression, which has been identified as a national shale oil demonstration area in China, are still unclear. In this study, the characteristics and the main controlling factors of reservoir differences in different sweet spots of Lucaogou Formation were specified based on core observation, thin-section observation, X-ray diffraction, Rock-Eval, microscopic fluorescence of hydrocarbon inclusions, and temperature measurement of saline inclusions. Results show that the Lucaogou Formation mainly develops dissolution and primary intergranular pores. The dissolution transformation leads to obvious differences between the upper and lower sweet spots. Specifically, the upper sweet spot section mainly develops primary intergranular pores and partially develops dissolution pores; the lower sweet spot section mainly develops dissolution pores, including intergranular, intragrain, and intergranular pores. Geochemical data such as inclusions indicate that hydrocarbon generation began in the Triassic, and a large number of hydrocarbons were charged in the Middle-Late Jurassic-Early Cretaceous. As the key fluid that triggers reservoir dissolution modification, it is mainly derived from organic acids generated by thermal evolution of source rocks within shale formations. The scale and quality of source rocks in the lower sweet spot are better than those in the upper sweet spot. The former has stronger hydrocarbon generation potential, which lays a foundation for the scale difference of organic acid output in the upper and lower sweet spots. At the same time, the source rocks in the lower sweet spot are more mature due to magmatic-hydrothermal upwelling. This condition accelerates the release of organic acids from source rocks, which results in the scale difference of dissolution effects in the upper and lower sweet spots.

1. Introduction

Shale oil is another new hotspot in the current global unconventional oil and gas exploration and development [1], and it has become one of the realistic strategic alternative resources. The Lucaogou Formation in the Jimsar Depression of the Junggar Basin has important shale oil exploration potential and mainly develops two sweet spot reservoir sec-

tions. Meanwhile, the complexity of the reservoir microscopic pore structure and its distribution mechanism restrict the reservoir quality and development effect [2, 3]. The reservoir space type and its genesis control the hydrocarbon storage and formation fluid percolation capacity [4]. Thus, understanding the characteristics of the reservoir space type and its main control factors in the sweet spot section of this study area is important. The pore types in this

study area are diverse, and the microscopic pore structure is complex. Previous studies have shown that primary intergranular pores, dissolution pores, intergranular pores, organic matter pores, and microfractures are mainly developed in this study area. Whether primary intergranular pores are considered to be equally developed with dissolution pores, or dissolution pores are considered to be dominant with the local presence of residual primary intergranular pores [5–7], a number of factors jointly govern the pore types of reservoirs in the study area, such as the superimposed modification of orogenic evolutionary reservoirs and the control of pore types by tectonic and hydrocarbon generation and deposition [3, 8–11]. Meanwhile, previous studies have shown differences in depositional environments, lithologic assemblages, hydrocarbon source rock maturity, and organic matter types in the upper and lower desert sections of the Lucaogou Formation, which inevitably result in different microscopic reservoir structures [12–15]. However, most scholars treat the study area as a complete set of shale reservoirs. Few studies distinguish the structural characteristics of shale reservoirs in the upper and lower sweet spots, and the studies further subdivide the spatial characteristics of the reservoirs in the upper and lower sweet spots and their constraints are insufficient. So, the differences in characteristics of reservoir and formation mechanisms between the upper and lower sweet spots of the Lucaogou Formation in the study area and the distribution pattern of high-quality shale oil reservoirs have not been clarified. Given that, the author explored the differences in microscopic pore characteristics, structures, and types between the upper and lower sweet spots of shale oil reservoirs based on the analysis of rock type differences between the upper and lower sweet spots by using core and cast thin-section observation, X-diffraction, and rock physical property analysis. Fluid inclusion system analysis (hydrocarbon inclusion microfluorescence and brine inclusion temperature measurement), Rock-Eval, and mirror reflectivity geochemical indexes are also used to clarify the formation mechanism of reservoir differences between the upper and lower sweet spots. Accordingly, this study provides exploration direction for the next high-quality sweet spot reservoirs in the study area and theoretical support for reservoir characterization of shale oil sweet spots.

2. Geological Setting

The Jimsar Depression is located in the southeastern part of the Junggar Basin, and it is bounded by the Jimsar Fault to the north, the Santai Fault to the south, and the Xidi Fault to the west. It gradually transitions to the Qitai Bulge to the east. It has undergone multiple periods of tectonic movements, including the Haixi, Indo-Chinese, and Yanshan-Himalayan periods, developing into the present tectonic pattern of deep west and shallow east, with the west broken and east overrun. The main target section of the Permian in the Jimsar Depression is the Lucaogou Formation, which has a stratigraphic thickness of 25–300 m, with an average of 200 m, and a burial depth of 800–4500 m, with an average

of 3570 m. The Lucaogou Formation is divided from bottom to top into two sets of one section (P_2l_1) and two sections (P_2l_2) of the Lucaogou Formation, which are each divided into two-layer groups; it has a total of four units: $P_2l_2^1$, $P_2l_2^2$, $P_2l_1^1$, and $P_2l_1^2$ (Figure 1). The Lucaogou Formation mainly develops two sedimentary systems of saline lake and delta phases, and seven sedimentary subphases of delta front, carbonate shallow, sandy shallow, cloud ping, mixed ping, mud ping, and semi-deep lake-deep lake [12–14, 16]. Many scholars have shown that the region is accompanied by volcanic activity and magmatic-hydrothermal upwelling in a large sedimentary context, which together act on the depositional environment. Ultimately, fine-grained mixed sedimentary rocks composed of terrestrial clastic, carbonate, and volcanic clastic components are formed [4, 17–21].

3. Samples and Methods

The samples were taken from the cores of six wells of the Lucaogou Formation in the Jimsar area, namely, J30, J251, J10025, J10024, J179, and J10005. Based on core observations, preliminary data, and full consideration of the need for subsequent experimental studies, intensive sampling was conducted in sweet spot at 1–2 m intervals for organic-rich and better-reservoir rock layers (Figure 1). The selected samples are evenly distributed in the sweet spot and are representative. This study mainly involves three items: characteristics of rock types in the sweet spot section, characteristics of reservoir space types and reservoir property, and its difference main control factors (Table 1).

The microfluorescence and temperature measurement of fluid inclusions in this experiment were all completed in the Key Laboratory of Tectonics and Petroleum Resources of the Ministry of Education, China University of Geosciences (Wuhan). The microfluorescence of hydrocarbon inclusions was collected and recorded using a Maya2000Pro spectrometer. The UV excitation wavelength was between 330 and 380 μm , and the room temperature was 20°C. The experimental instrument for microscopic temperature measurement of salt water inclusions is THMS600 liquid nitrogen type hot and cold stage, the temperature error is $\pm 0.1^\circ\text{C}$, and it complies with SY/T6010-2011 and other standards. The cold cathode luminescence model is RELION CL6, the test conditions are 10 kV and 500 μA , the indoor temperature is 20°C, and the rock mineral cathodoluminescence identification method is complied with standard number SY/T5916-2013. Rock pyrolysis and organic carbon quality geochemical analysis were performed in the Oil and Gas Geochemistry Laboratory of Yangtze University by using rock pyrolysis instrument OGE-VI and carbon and sulfur analyzer CS230, respectively.

4. Results

4.1. Mineral Composition Characteristics of Sweet Spot Rocks. In this study, 75 samples were tested and identified by X-ray diffraction: 34 samples of the upper sweet spot and 41 samples of the lower sweet spot. The results indicate that the Lucaogou Formation mainly develops (iron) dolomite,

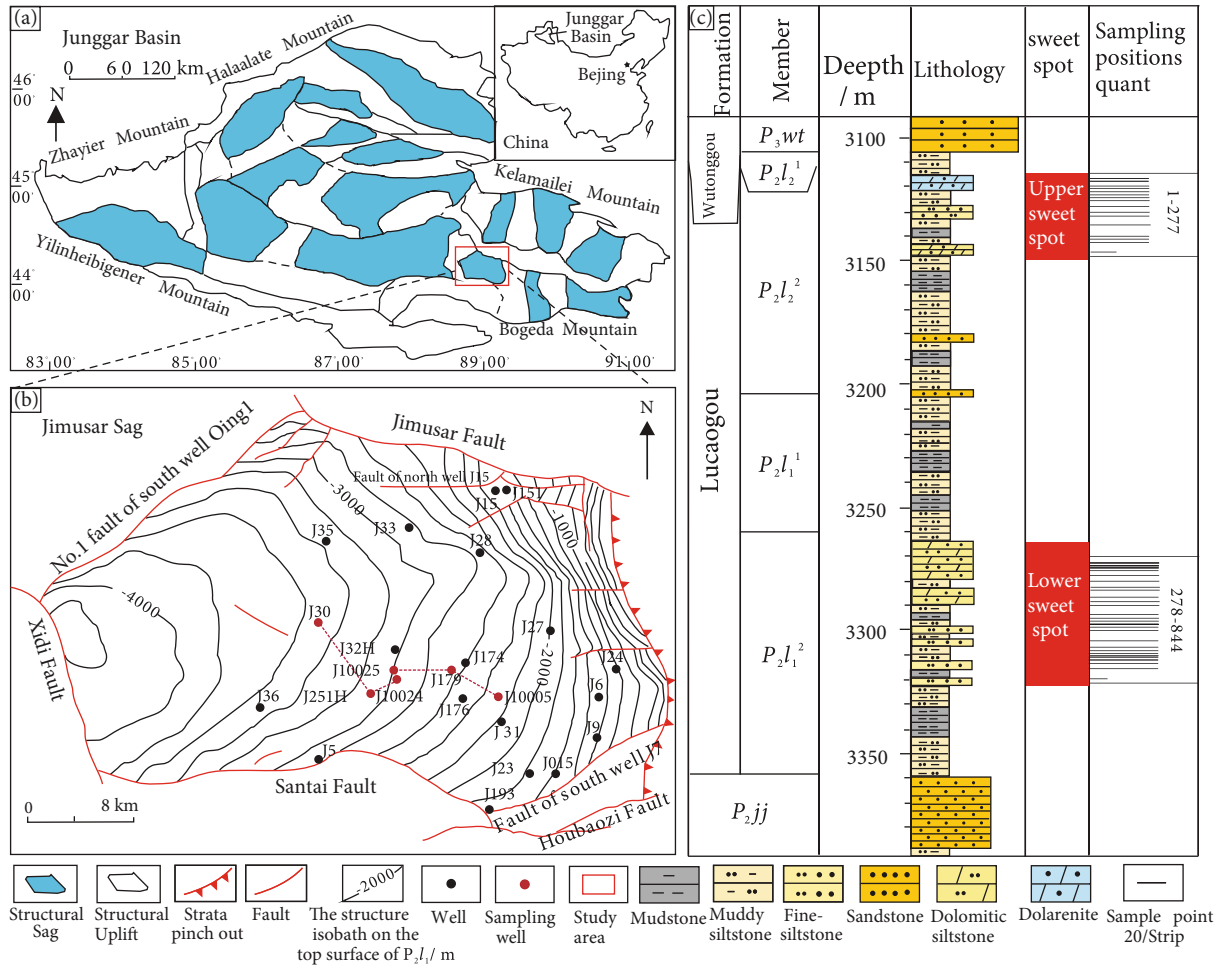


FIGURE 1: Location of the Jimsar Sag in the Junggar Basin (a). Structure contour map of the Middle Permian Lucaogou Formation in the Jimsar Sag (b). Stratigraphic column of the Lucaogou Formation and location of the samples (c) (modified from Xi et al., 2015 and Liu et al., 2019).

feldspar, and quartz, and it has less clay and locally developed pyrite. The vertical distribution characteristics of rock mineral components in the upper and lower sweet spots were drawn from 44 samples of single well J10025 in Lucaogou Formation in Jimsar Sag (24 samples of upper sweet spot and 18 samples of lower sweet spot). The results mark that the content of mineral components varies greatly and changes frequently with depth. The X-diffraction results were further divided into clastic and carbonate rocks to compare the difference characteristics of the main mineral composition of different rock types in the upper and lower desert sections. The results show that the content of feldspar fractions composing clastic and carbonate rocks is higher in the upper desert than the lower desert, and the difference between the upper and lower desert is smaller for dolomite fractions (Figure 2).

4.2. Characteristics of Rock Types

4.2.1. Characteristics of Rock Types in the Sweet Spot. The identification results of rock and cast thin sections suggest that the Lucaogou Formation mainly develops mud-

stone, shale, dolomite, siltstone, and fine sandstone. As the main reservoir rocks, dolomite, siltstone, and fine sandstone are further divided into silty dolomite, calcareous dolomite, argillaceous dolomite, argillaceous siltstone, and very fine-grained feldspar sandstone (Figures 3(a), 3(b), 3(c), 3(d), 3(e), 3(f), and 3(g)). As the main source rocks, mudstone and shale are divided into silty mud (shale) rock, dolomitic mud (shale) rock, and calcareous mud (shale) rock (Figures 3(h), 3(i), 3(j), 3(k), and 3(l)). The source and reservoir rocks of the Lucaogou Formation are produced in an interbedded manner, with the hydrocarbon source rocks producing oil and the reservoir rocks storing oil. The source and reservoir are integrated or interbedded, which forms a distinctive interlayer-enriched shale oil [15, 22].

On the basis of thin sections and X-ray diffraction, the reservoir rocks can be divided into two major components: clastic and carbonate rocks. The clastic rocks are dominated by fine sandstone and siltstone composed of feldspar and quartz (Figure 3(d)). The carbonate rocks are mainly dolomite, and the dolomite grains are generally small and mainly micrite-microcrystalline (Figure 3(g)).

TABLE 1: The summary of sample distribution characteristics and test types.

Research purpose	Differential characteristics of sweet spot reservoir			Differential formation mechanism of sweet spot reservoir									
	Reservoir rock types, reservoir space, and performance differences	Reservoir rock	Hydrocarbon charging and acid fluid release characteristics	Hydrocarbon charging and acid fluid release	Differences in size, quality, and thermal evolution of source rocks	Source rock							
Sample lithology	Source rock/reservoir rock	Reservoir rock	Calcite vein/speckled calcite										
Upper sweet spot	1-34 (34)	35-50 (16)	51-105 (55)	106-205 (100)	206-209 (4)	—	—	210-260 (51)	261-267 (7)	268-277 (10)	—		
The distribution layer	278-318 (41)	319-336 (18)	337-414 (78)	415-714 (300)	715-723 (9)	724-733 (10)	734-743 (10)	744-753 (10)	754-819 (66)	820-828 (9)	829-844 (16)	—	
Lower sweet spot	34	133	400	13	10	10	10	117	16	26	—	—	
Count													
Experiment	X-ray diffraction (XRD)	Rock thin sections	The casting thin sections	Helium porosity method▲	SEM-EDS	CL	Microscopic fluorescence	Microthermometry of fluid inclusions	Organic carbon content	S ₁ + S ₂	Type of organic matter	R _o (plane)●	R _o (portrait)◆

Helium porosity data is from Xinjiang Oilfield Company. Plane R_o data is from Liu et al. (2019) and portrait R_o data is from Qiu et al. (2016). The numbers in the first column are shown in Figure 2.

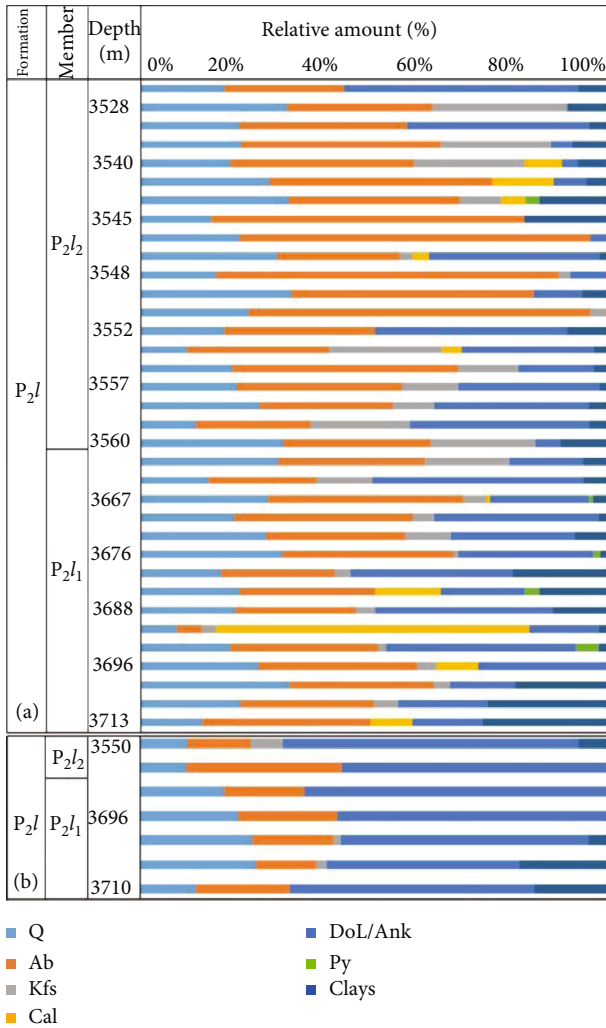


FIGURE 2: Longitudinal distribution characteristics of the main mineral components in the upper and lower sweet spots of well J10025: clastic rocks (a) and carbonate rocks (b).

4.2.2. *Differences in Rock Types in the Sweet Spot.* The distribution of reservoir lithology in the upper and lower sweet spots in the Lucaogou Formation of Jimsar Sag differs due to the difference in sedimentary environment. The fine-grained sandstones are mainly developed in the upper sweet spot, and they are mainly ultra-fine-grained feldspar sandstones (Figure 3(a)). Siltstones are mainly developed in the lower sweet spot (Figures 3(e) and 3(f)). They are mostly argillaceous siltstone and dolomitic siltstone (Figures 3(d) and 3(e)), with a small amount in the upper sweet spot, such as argillaceous siltstone (Figure 3(b)). Dolomites are distributed in the upper and lower sweet spots (Figures 3(c), 3(d), and 3(g)), and they are mainly divided into silty dolomite, argillaceous dolomite, and calcareous dolomite.

4.3. *Differences in Physical Properties of Sweet Spots.* Five wells, J10022, J10025, J305, J10016, and J174, were longitudinally selected for physical property analysis of the upper and lower sweet spot reservoir rocks in order to clarify the reser-

voir properties of different rock types in the upper and lower sweet spot reservoirs and the difference characteristics of the same lithology in the upper and lower sweet spot reservoirs. The results show that the porosity of the siltstone in the upper sweet spot of the Lucaogou Formation is 12.56% and that of the dolomite is 7.80%. The porosity of the siltstone in the lower sweet spot reaches 14.11%, and the porosity of the dolomite in the lower sweet spot reaches 12.95%, which is higher than the average porosity of the siltstone in the upper sweet spot (Figure 4). The lithologic porosity of the lower sweet spot is higher than that of the upper sweet spot, and the total porosity of clastic rocks is higher than that of carbonate rocks. The porosity of siltstone is high, followed by that of fine sandstone, and dolomite has the smallest porosity.

4.4. *Differences in Pore Types in Sweet Spots*

4.4.1. *Reservoir Space Types and Differences.* According to the observation results of cast thin sections, secondary dissolution pores are mainly developed in the Lucaogou Formation, and primary intergranular pores and microfractures are developed in part.

(1) Secondary dissolution pores

Secondary dissolution pores, including intergranular, intragranular, and intercrystalline dissolved pores, are the main type of pores in the Lucaogou Formation reservoir in Jimsar Sag (Figure 5). Among the three, intergranular dissolved pores are the most developed. The degree of development of dissolution pores is closely related to unstable minerals such as feldspar, dolomite, and calcite, as well as the process of hydrocarbon generation and expulsion. The dissolution effect of feldspar is the strongest, and it is easy to occur along the sodium feldspar dissolution joints and other parts of the dissolution. Honeycomb-like dissolution pores are formed in the strong dissolution zone (Figure 5(d)). Intercrystalline dissolved pores are generally smaller in diameter and mainly developed in unstable minerals such as dolomite and calcite (Figures 5(b), 5(c), 5(e), and 5(f)).

(2) Primary intergranular pore space

The primary intergranular pores have clear edges and are mostly triangular and quadrilateral (Figures 5(a) and 5(g)). The primary intergranular pores are mainly developed in the fine sandstone and siltstone of the upper sweet spot.

(3) Microcracks

Microfractures are locally developed in the study area, and they are mainly divided into structural and bedding fractures: the structural fractures are mostly high-angle fractures and cut through the bedding; the bedding fractures extend along the bedding plane at a low angle or horizontal direction with a width of about 10 μm and a wider area of about 20 μm, and they mainly exist in mud shale (Figure 5(f)).

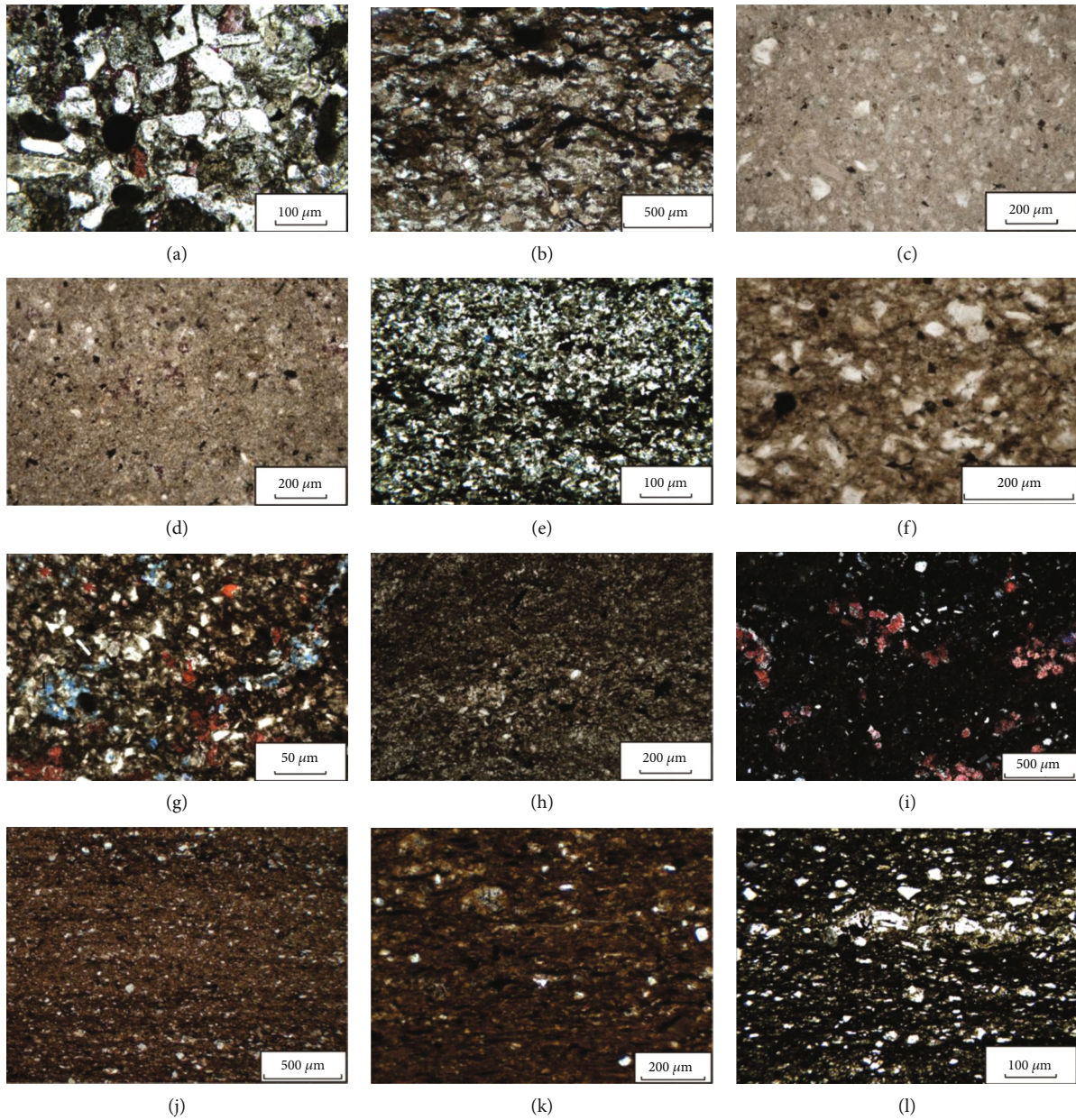


FIGURE 3: Characteristics of rock types of Lucaogou Formation in Jimsar Sag: (a) very fine feldspar lithic sandstone, basalt lithic debris, and other magmatic rock debris (J10005, 2692.55 m, P_2I_2); (b) argillaceous siltstone, visible quartz, and feldspar (J10025, 3544.68 m, P_2I_2); (c) silty dolomite (J30, 4046.74 m, P_2I_2); (d) argillaceous dolomite (J251, 3618.64 m, P_2I_2); (e) muddy siltstone, mainly fine silt, granular quartz, feldspar mainly plagioclase, and poor particle roundness (J10024, 3631.72 m, P_2I_1); (f) dolomite siltstone, dominated by feldspar, subangular (J10024, 3624.52 m, P_2I_1); (g) silt-bearing calcareous dolomite, mainly dolomite of a mud-microcrystalline structure with fine grains (J10005, 2813.56 m, P_2I_1); (h) dolomitic shale, horizontal bedding (J10024, 3636.52 m, P_2I_1); (i) calcareous mudstone, organic matter, and clay are mixed together and filled between siltstones, and the clay is dyed dark brown and black by organic matter (J10022, 3487.33 m, P_2I_1); (j) silty mudstone (J10024, 3619.02 m, P_2I_1); (k) dolomitic mudstone, clay is reddish brown by oil and gas disseminated (J10025, 3530.91 m, P_2I_2); (l) silty shale, mainly fine silt, organic matter, and clay-oriented arrangement and silt interbedded to form layers (J10024, 3484.03 m, P_2I_2).

4.4.2. *Differences in Characteristics of Dissolution Pores in the Sweet Spot.* The quantitative comparison and analysis of various types of dissolved pore data of different rock types in the upper and lower sweet spots were conducted. The grid method was used to make quantitative statistics of reservoir karstic erosion in this reservoir unit, and then, the proportions of different pore types in the same lithology in the

same sweet spot were further analyzed. The results show that intergranular and intragranular dissolved pores account for 87.50% of the total pore volume of siltstone in the lower desert point formation. The dissolution pores of dolomite in the lower sweet spot reservoir account for 96.67% of the total pore volume. In the upper sweet spot clastic rock, the intragranular dissolved pores account for 11.67%-32.50%, the

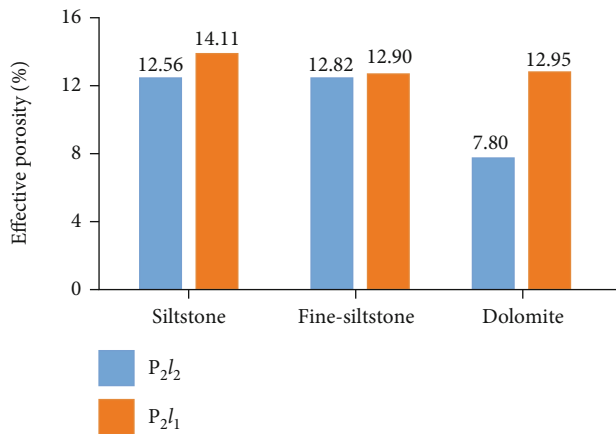


FIGURE 4: Effective porosity (%) of each lithology in the upper and lower sweet spots.

intergranular dissolved pores account for 7.22%-21.50%, and the primary remaining intergranular pores account for 40.00%-80.33%. The carbonate rocks in the upper sweet spot, such as dolomite, mainly develop intercrystalline dissolved pores, with local dissolution fractures (Figures 6(a) and 6(b)). The dissolution pores of the upper and lower sweet spots obviously differ, and the dissolution intensity of the lower sweet spot is higher than that of the upper sweet spot.

The analysis suggests that the development matrix and degree of secondary dissolution pores, as the main pore type in the study area, obviously differ in the upper and lower sweet spots. Specifically, secondary dissolution pores are generally developed in the siltstone reservoir rocks of the lower sweet spot, and they are partly developed in the dolomite of the upper and lower sweet spots (Figures 6(a) and 6(b)). The primary intergranular pores are mainly developed in the fine sandstone and siltstone of the upper sweet spot member (Figure 6(a)). Meanwhile, the primary intergranular pores in the lower sweet spot siltstone and dolomite reservoirs disappear or are dissolved into intergranular solution pores.

4.5. Characteristics of Dissolution Fluid in Sweet Spots. X-ray diffraction and cast thin sections show a large number of soluble components such as feldspar in the upper and lower sweet spots, but the dissolution degree of siltstone in the lower sweet spot is significantly stronger than that of fine-grained sandstone and siltstone in the upper sweet spot. Dissolution is mainly related to organic acids released in the process of hydrocarbon generation and expulsion, carbonic acid formed by CO₂ dissociated from organic acids at high temperature and dissolved in atmospheric water or underground water, and acidic water formed by clay mineral transformation. Secondary dissolved pores formed by inorganic acids produced during the transformation of Aemon/montmorillonite are not easily preserved [10]. At the same time, fresh water deposits are observed in the upper sweet spot of the study area, and the current trend

of secondary dissolution pores shows that the dissolution of the lower sweet spot with deeper burial is more intense. This condition is in contrast to the fresh water leaching, which indicates that the filtration of fresh water forest is not the factor causing the difference in dissolution in the upper and lower sweet spots. The effect of atmospheric freshwater leaching is naturally excluded, and previous work has also shown that atmospheric freshwater has no significant modifying effect on reservoirs [10, 14, 23]. Organic acids have 6-350 times the dissolving power of carbonic acid [24]. Large stacked sedimentary basins in China usually contain multiple layers of hydrocarbon source rocks, and the reservoirs adjacent to hydrocarbon source rocks are usually dissolved by hydrocarbon-related acidic fluids. This phenomenon results in dissolution in shale oil desert reservoirs being different from that in conventional oil and gas reservoirs. Especially for the source-reservoir interbedded or integrated characteristics of the Lucaogou Formation, more consideration should be given to the mutual influence between the two [25, 26]. The classical theory of hydrocarbon generation and recent studies also show that a certain amount of organic acids and CO₂ can be generated at early to middle maturity [27], and carboxylic acids and CO₂ can be generated even at late maturity when H₂O and inorganic minerals are involved in hydrocarbon generation [28-30].

Many scholars believe that the dissolution of reservoir-soluble components by organic acids during the maturation of hydrocarbon source rocks is an important mechanism for the generation of large-scale secondary dissolution pores during the formation of reservoirs. Hu et al. attributed the massive development of dissolution pores in the Lucaogou Formation to the dissolution of organic acids formed in the process of thermal evolution of source rocks. Meanwhile, previous authors have used evidence such as oil-filled secondary pores with coexisting hydrocarbons and bright yellow fluorescence to suggest that secondary pores are the result of hydrocarbon fluid filling interactions. Wu et al. provided direct evidence of hydrocarbon-associated fluid dissolution using fluorescence images showing the coexistence of secondary pores with hydrocarbons producing bright yellow fluorescence [14, 24, 31-34]. In the current study, a large number of feldspar, quartz, dolomite, and other mineral particles are seriously infected by organic matter in the cast thin section and under scanning electron microscope, and organic acids are released to directly dissolve the particles with the increase in organic matter maturation (Figures 5(b), 5(e), 5(h), and 5(i)). The exploration shows that the dissolved fluids in this study area are mainly organic acids generated by the thermal evolution of organic matter.

4.5.1. Division of Hydrocarbon Charging Stages in Sweet Spots. The observation of core fractures and holes suggests that the core fractures and holes in the lower sweet spot of the study area are mostly filled with calcite, which forms parallel-layered calcite veins, high-angle calcite veins, and speckled calcite filled with holes (Figures 7(a) and 7(d)). The microlithography, cathode luminescence, and filling

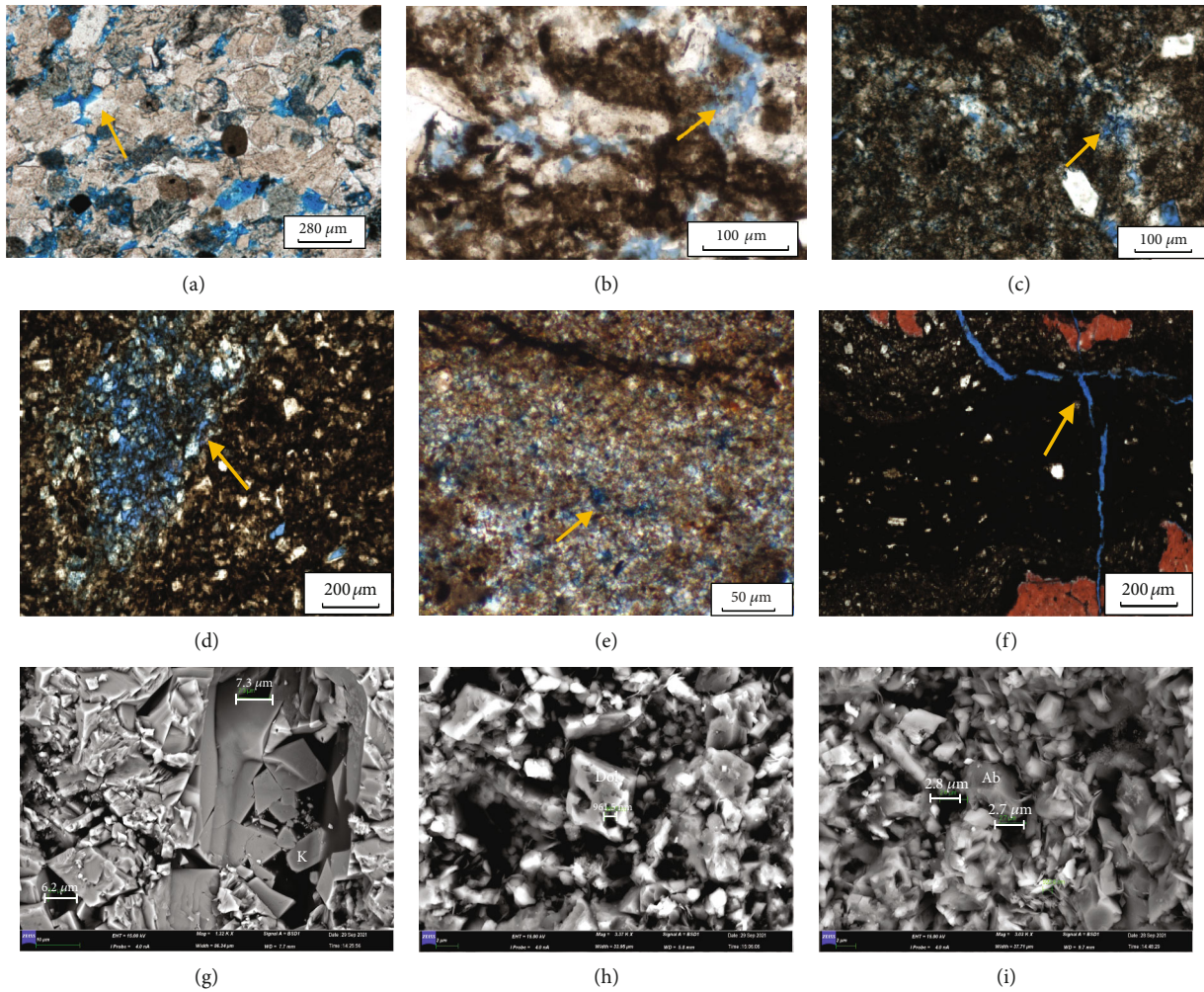


FIGURE 5: Different pore structure characteristics of Lucaogou Formation in Jimsar Sag: (a) fine-grained sandstone, with primary pores (J10025, 3555.08 m, P_2l_2); (b) argillaceous siltstone, feldspar particles, and interstitials are dissolved, and intergranular dissolved and intragranular dissolved pores are developed (J10025, 3548.65 m, P_2l_2); (c) micrite silt containing silt dolomite, intercrystalline dissolved pores, and feldspar particles are dissolved into intragranular dissolved pores (J100024, 3484 m, P_2l_2); (d) dolomitic siltstone and feldspar forms honeycomb dissolved pores (J10025, 3697.7 m, P_2l_1); (e) muddy silt-containing dolomite, intergranular dissolved pores, and intragranular dissolved pores (J10024, 3641.12 m, P_2l_1); (f) siltstone sand-calcareous shale, two intersecting microfractures (J10025, 3708.18 m, P_2l_1); (g) argillaceous siltstone, primary intergranular pores are formed between dolomite and feldspar (J10025, 3555.48 m, P_2l_2); (h) dolomitic siltstone, dolomite, and feldspar are dissolved, intergranular dissolved pores, intragranular pores, and dissolution pores (J10024, 3642.39 m, P_2l_1); (i) argillaceous siltstone, feldspar is dissolved, intergranular dissolved pores (J10024, 3631.77 m, P_2l_1).

characteristics of 10 samples from the lower sweet spot member of Lucaogou Formation were tested. The results indicate that the cathode luminescence of calcite minerals is mainly dark red and bright orange yellow. The mineral characteristics and cutting relationship of calcite under transmission light also reveal two stages of fluid charging for each type of calcite filling structure. In the early stage, it is filled with cracks and pores on a scale and appears dark red under cathodoluminescence. It is an early fluid characteristic and directly contacts clay minerals. The late stage is filled with calcite in the early residual space, which is orange-yellow under cathodoluminescence (the gap closed), and the late-stage fluid enters along the early vein body gap (Figures 7(b), 7(c), 7(e), and 7(f)). The main charging period

of hydrocarbons in Lucaogou Formation was determined by fluorescence spectra of hydrocarbon inclusions captured by calcite of different occurrences and analysis of saline inclusions associated with hydrocarbons.

(1) Petrographic characteristics of fluid inclusions

Transmission light and fluorescence microspectral observation show that fluid inclusions are abundant in shale reservoirs of Lucaogou Formation in Jimsar Sag. The inclusions are elongated, elliptic, and irregular. According to the phase state and composition characteristics of the inclusions, the inclusions can be divided into two types: gas-liquid two-phase and single liquid phase. The inclusions are mainly

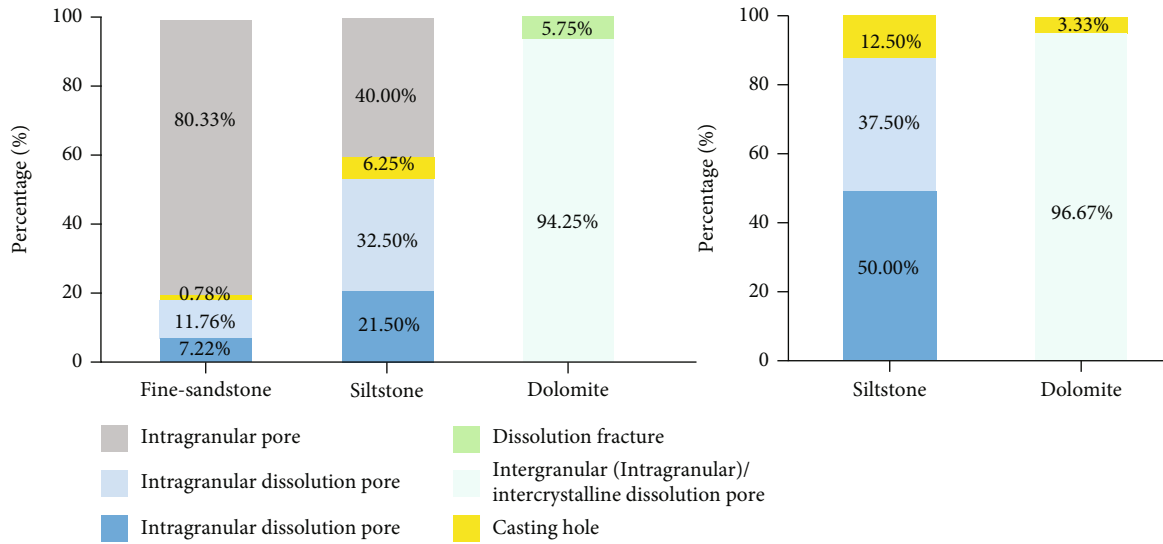


FIGURE 6: Comparison of different types of lithologies and storage spaces in the upper and lower sweet spots.

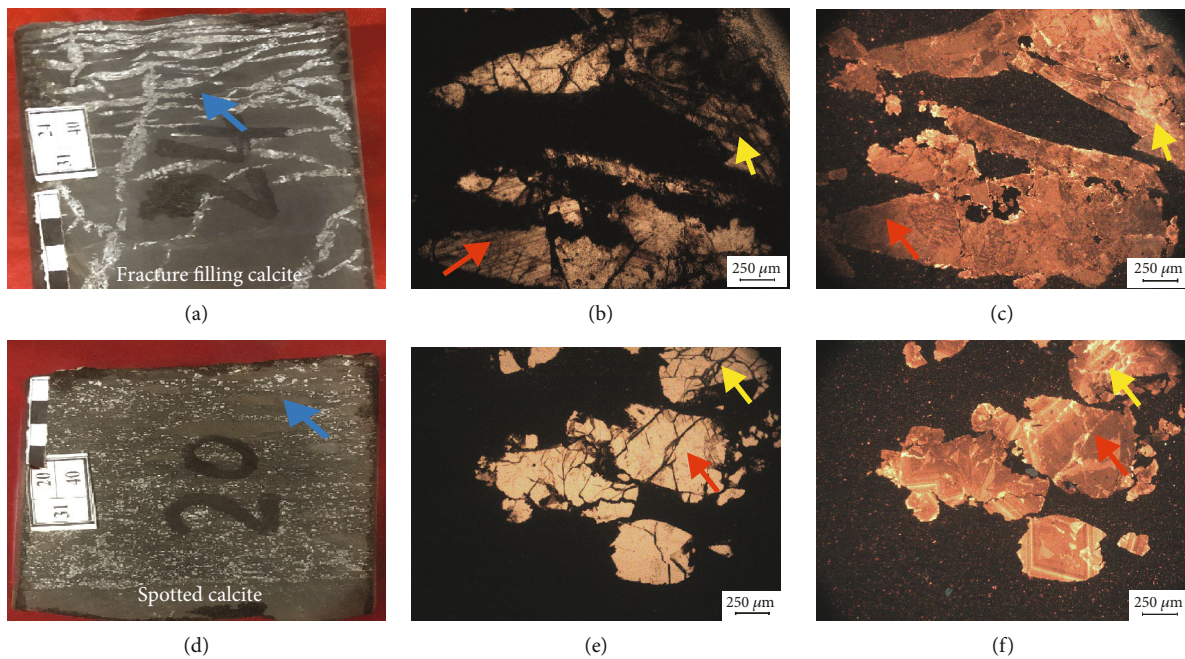


FIGURE 7: Characteristics of calcite of different occurrences in Lucaogou Formation, Jimsar Sag: (a) fracture filling calcite (J10025, 3707.9 m, P_2l_1); (b) colorless under single polarized light (J10025, 3707.9 m, P_2l_1); (c) dark red (red arrow) and orange yellow (yellow arrow) under cathode luminescence (J10025, 3707.9 m, P_2l_1); (d) spotted calcite (J10025, 3707.7 m, P_2l_1); (e) colorless under single polarized light (J10025, 3707.7 m, P_2l_1); (f) dark red (red arrow) and orange yellow (yellow arrow) under cathode luminescence (J10025, 3707.7 m, P_2l_1).

gas-liquid two-phase hydrocarbon inclusions, and some of them are single liquid phase hydrocarbon inclusions. Previous studies have shown that the maturity of generated hydrocarbons increases and the fluorescence colors of captured hydrocarbon inclusions are red-orange, yellow, yellow-green, and blue-white in sequence with the increase in thermal evolution of organic matter [34, 35]. The hydrocarbon inclusions in the sweet spot section of the study area exhibit yellow, orange, yellow-green, and blue-white fluorescence

under IV excitation. Among them, orange and yellow are dominant, and some are yellow-green (Figure 8). Brine inclusions are mainly divided into secondary brine inclusions and primary brine inclusions associated with hydrocarbon inclusions. Secondary saline inclusions are mostly distributed in beaded forms along the fracture (Figures 9(a) and 9(b)), while primary saline inclusions are mostly distributed in circular bands or isolated forms along the growth zone (Figures 9(c) and 9(d)).

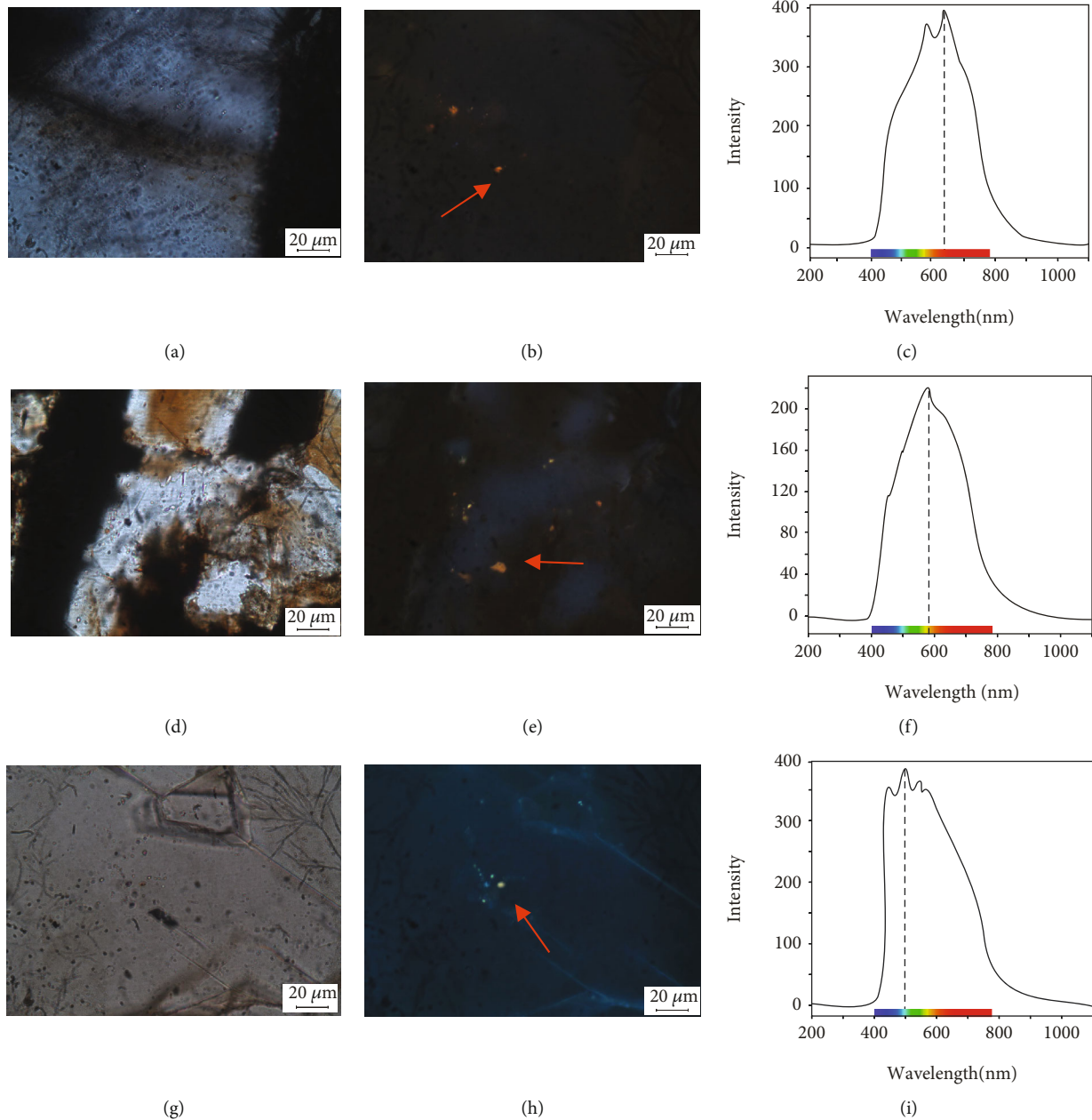


FIGURE 8: Microfluorescence and spectral characteristics of hydrocarbon inclusions captured by calcite in Lucaogou Formation, Jimsar Sag.

(2) Hydrocarbon charging characteristics

The charging time and times of hydrocarbon inclusions were classified by combining the homogeneous temperature of secondary brine inclusions associated with hydrocarbon inclusions and the microfluorescence characteristics of hydrocarbon inclusions. The microscopic fluorescence of hydrocarbon inclusions shows that the study area is dominated by first-stage hydrocarbon charging, which is mainly yellow fluorescence inclusions. Homogenization temperature of secondary brine inclusions shows that it is distributed from 60°C to 140°C, the main peak value appears at 70°C to 80°C, and the secondary peak value appears at 110°C to

120°C and 130°C to 140°C (Figure 10(a)). The combined thermal evolution-burial history map indicates that the hydrocarbon source rocks in this study area started to produce hydrocarbons from the Triassic, and the Middle-Late Jurassic-Early Cretaceous were heavily filled with hydrocarbons and lasted for a long time (Figure 10(b)).

4.6. Release Characteristics of Organic Acids in Desert Segment. In the process of thermal maturation of hydrocarbon source rocks, a large amount of organic acid and CO₂ will be produced due to decarboxylation, the pore fluid pH value will decrease, and the rock formation environment will change to weak acidic-acidic. This phenomenon will dissolve

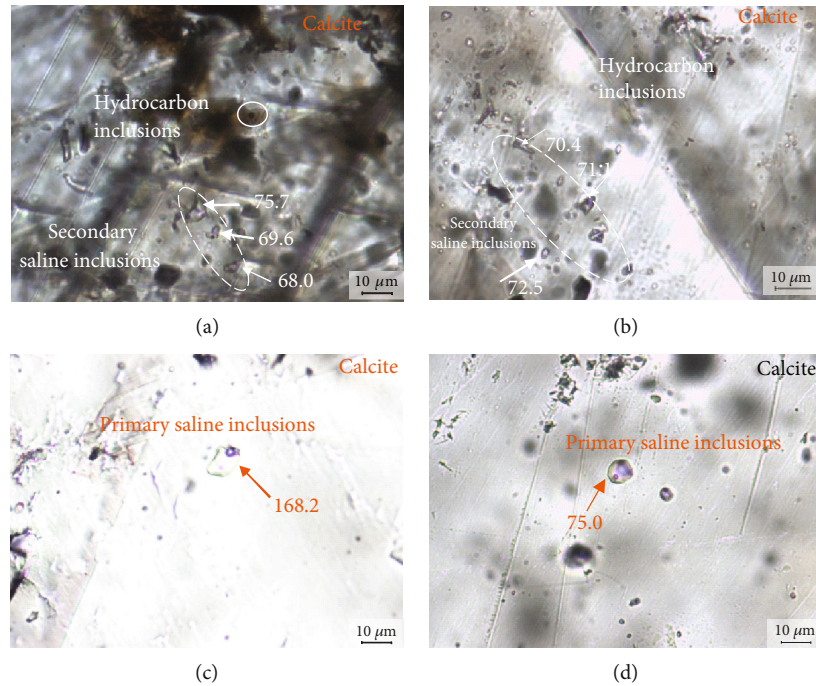


FIGURE 9: Microscopic characteristics of saline inclusions captured by calcite in Lucaogou Formation, Jimsar Sag: (a) the secondary saline inclusions were beaded (J10025, 3694.32 m, P_2I_1); (b) the secondary saline inclusions were beaded (J10024, 3634.52 m, P_2I_1); (c) primary saline inclusions are isolated (J10025, 3706.51 m, P_2I_1); (d) primary saline inclusions are isolated (J10024, 3634.52 m, P_2I_1).

the unstable mineral components in the organic-rich shale and nearby rocks and produce dissolved pore space. Reservoir rocks such as sandstones and siltstones in the study area are frequently interbedded with organic-rich mudstones or even wrapped in source rocks, which are easy to become drainage channels of acidic hydrocarbon-forming fluids. The activity of acidic fluid is often related to hydrocarbon generation and accumulation stages because the acidic fluid in diagenetic environment is mainly related to organic acids in the process of hydrocarbon generation of source rocks. As observed from hydrocarbon charging, organic acids begin to generate hydrocarbons with the Triassic source rocks (Figure 10(b)), which erodes the soluble substrates such as feldspar and dolomite. Middle-Late Jurassic-Early Cretaceous scale hydrocarbon charging increases the organic acid production and the dissolution scale, which results in the most intense dissolution in this stage.

5. Discussion

The development of dissolution pores in the study area is the result of the beginning of hydrocarbon generation of Triassic source rocks and the maturity of Middle-Late Jurassic-Early Cretaceous source rocks to produce organic acids of scale. The hydrocarbon expulsion efficiency of organic acid production is related to the difference in hydrocarbon generation potential and thermal evolution degree of source rocks. In view of the dissolution intensity of the lower sweet spot is stronger than that of the upper sweet spot, the author will discuss the dissolution pore difference mechanism of different sweet spots from the perspective of the organic acid

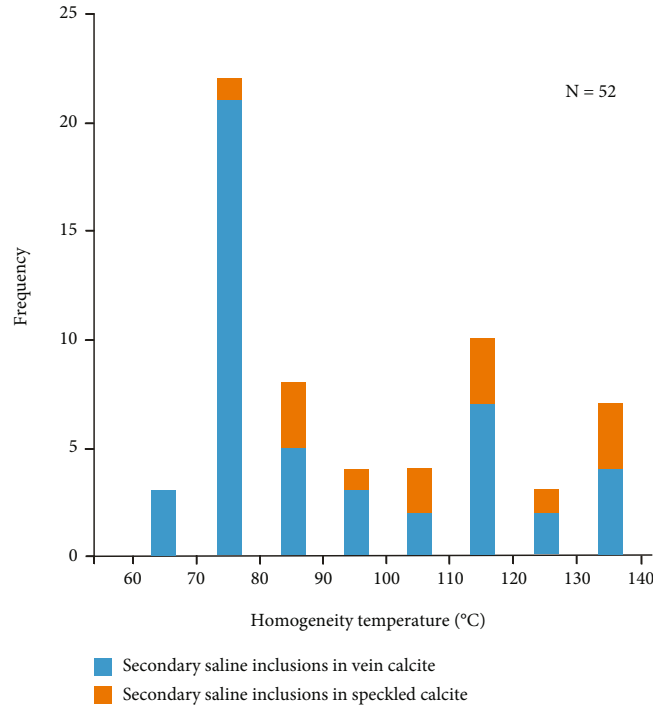
production difference under the background of source-reservoir integration or interlayer of shale oil.

5.1. Differences in the Development of Source Rocks in the Sweet Spot

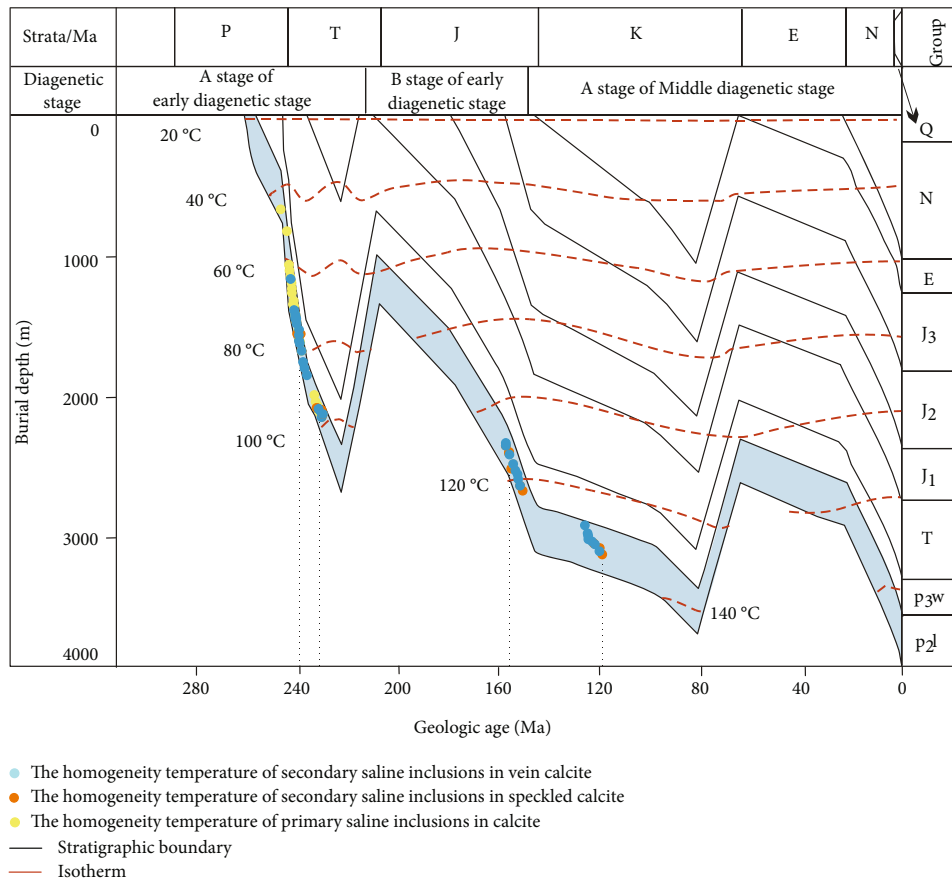
5.1.1. Scale Difference Characteristics of Source Rocks. The scale development of source rocks is the basis of hydrocarbon generation and organic acid production. Previous studies have shown that source rocks in the upper and lower desert sections of the Lucaogou Formation have a certain distribution range and thickness but have differences. The favorable area of source rocks in the upper sweet spot with a thickness greater than 5 m is about 398 km² with an average thickness of 24.8 m. The favorable area of source rocks in the lower sweet spot with a thickness greater than 20 m is about 871 km² with an average thickness of 34.8 m [18]. The favorable area distribution of source rocks in the lower sweet spot is wider and thicker, and the overall development scale is larger than that in the upper sweet spot.

5.1.2. Quality Difference Characteristics of Source Rocks

(1) Differences in characteristics of total organic carbon. The abundance of organic matter is an important determinant of hydrocarbon generation potential and intensity. Total organic carbon content is widely used to indicate the abundance of organic matter. In this study, the total organic carbon contents of source rocks from Lucaogou Formation were measured, including 51 samples from upper sweet spot and 66 samples from lower sweet spot. According to the evaluation standard of clastic and carbonate source rocks



(a)



(b)

FIGURE 10: Histogram of homogenization temperature of secondary saline inclusions (a). Projection of burial history and thermal evolution in Jimsar Depression (b).

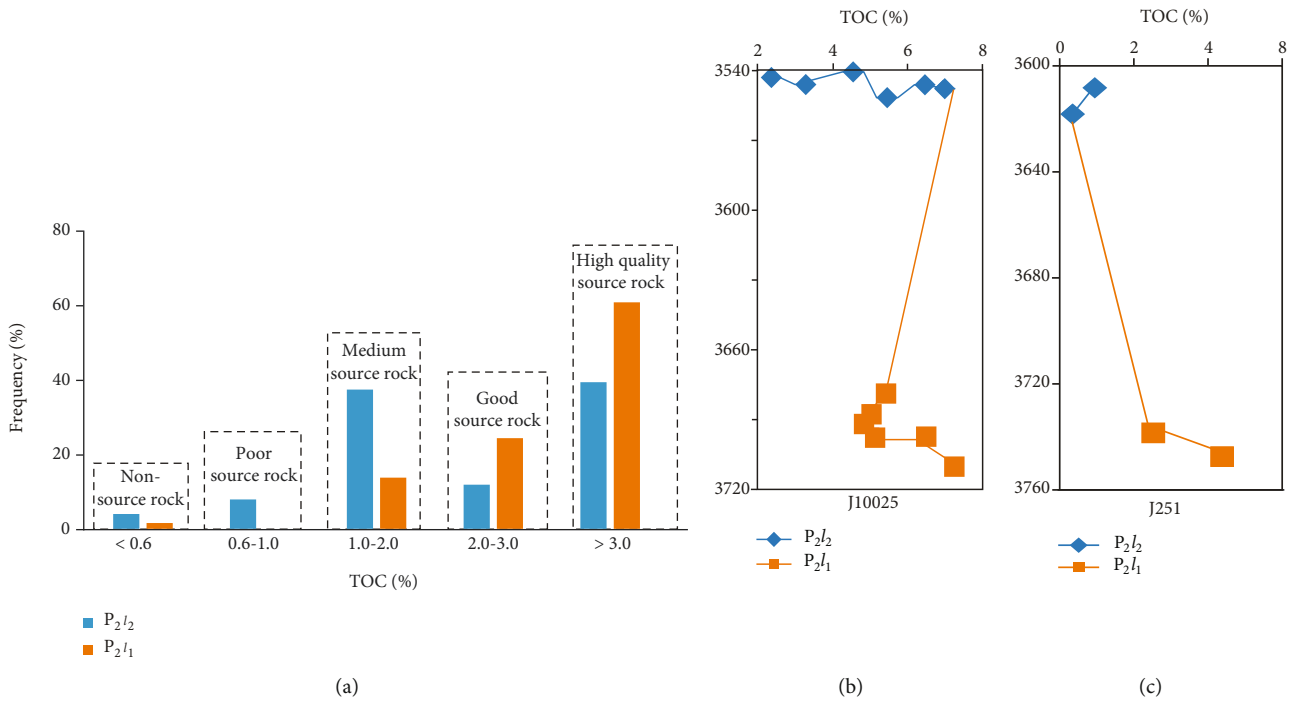


FIGURE 11: Total organic carbon content characteristics of source rocks in Lucaogou Formation, Jimsar Sag (a). Distribution characteristics of organic matter in the upper and lower sweet spots of single wells J10025 and J251 (b) and (c), respectively.

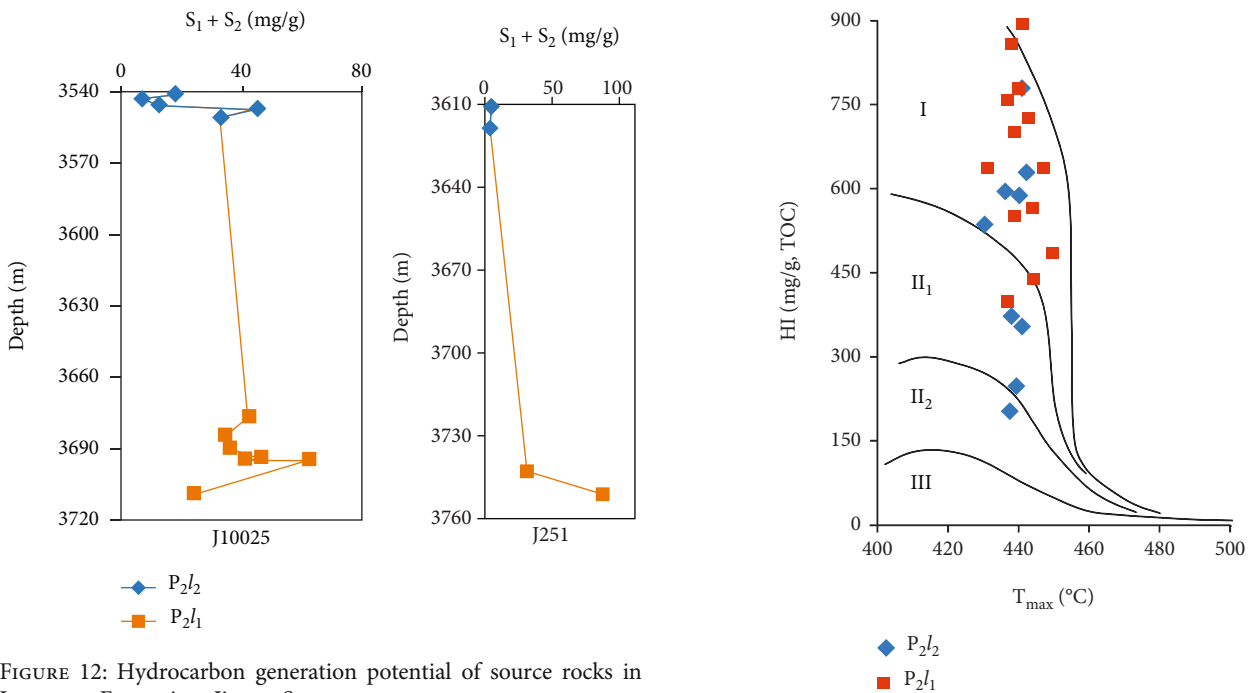


FIGURE 12: Hydrocarbon generation potential of source rocks in Lucaogou Formation, Jimsar Sag.

FIGURE 13: Organic matter types in the upper and lower sweet spots of source rocks in Lucaogou Formation, Jimsar Sag.

(SY/T5735-2019), the source rocks measured in this study can be divided into nonsource rocks, poor source rocks, medium source rocks, good source rocks, and high-quality source rocks. The data show that the total organic carbon content of the source rocks in the sweet spot is good, and the organic matter is good, with strong hydrocarbon generation potential. The source rocks in the upper and lower

sweet spots differ. The high-quality source rocks in the lower sweet spot have a higher frequency of distribution and are mainly high-quality source rocks, while the upper sweet spot is mainly composed of high-quality and medium-sized

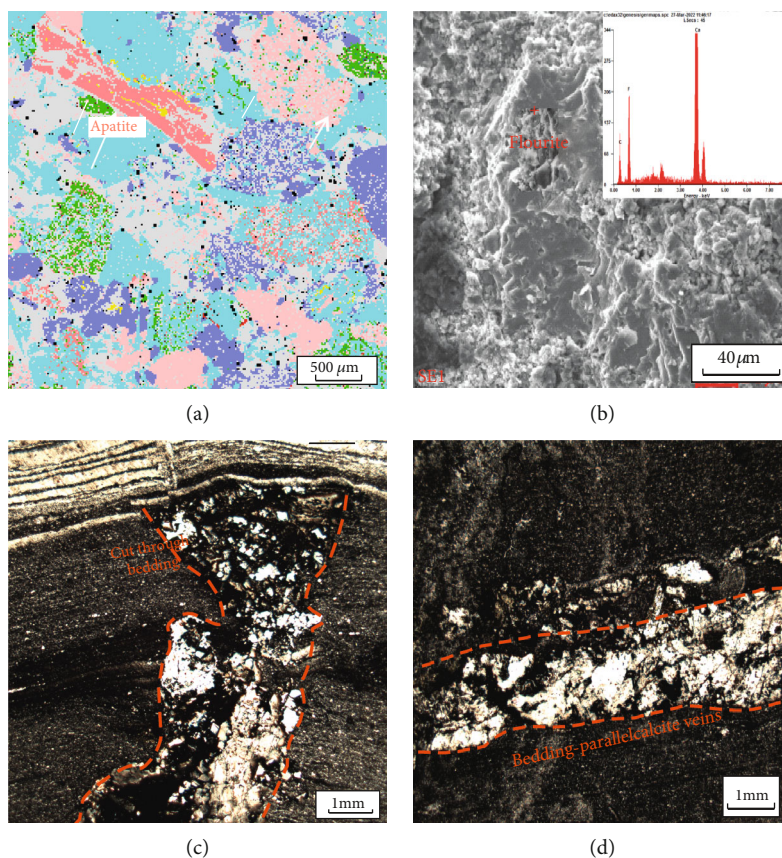


FIGURE 14: Characteristics of magmatic-hydrothermal mineral composition in Lucaogou Formation, Jimsar Sag.

source rocks (Figure 11(a)). The single well diagram shows total organic carbon content of source rocks in the lower sweet spot is higher than that in the upper sweet spot (Figures 11(b) and 11(c)). From this, we can conclude that the organic matter abundance is higher than that in the upper sweet spot.

(2) *Differences in characteristics of hydrocarbon generation potential ($S_1 + S_2$).* Calculation of hydrocarbon generation potential is an important factor for evaluating hydrocarbon generation potential of source rocks. In this study, the potential hydrocarbon generation characteristics of source rock samples from well J0025 and well J251 in Lucaogou Formation were tested, including 7 upper sweet spot data and 9 lower sweet spot data. The data of hydrocarbon generation potential ($S_1 + S_2$) mark that the hydrocarbon generation potential ($S_1 + S_2$) of the lower sweet spot is between 3.69 and 44.82 mg/g with an average of 23.64 mg/g, and the hydrocarbon generation potential ($S_1 + S_2$) of the upper sweet spot is between 23.97 and 80.87 mg/g with an average of 43.93 mg/g. A certain hydrocarbon generation potential is observed in the upper and lower sweet spots, and the single well diagram shows that the hydrocarbon generation potential in the lower sweet spots is higher than that in the upper sweet spots (Figures 12(a) and 12(b)).

(3) *Differences in characteristics of organic matter types.* The type of kerogen has obvious control effect on the production

of organic acids. The acid generation of type III kerogen source rocks is significantly lower than that of type I and type II kerogen, and hydrocarbon source rocks with organic matter types dominated by type I and II have strong acid-generating capacity [36]. In this study, 26 source rock samples of Lucaogou Formation from five wells J179, J10005, J10024, J0025, and J251 were tested, and they include 16 lower sweet spot and 10 upper sweet spot data. The types of organic matter kerogen in the study interval are mainly type I and type I-II₁ (Figure 13), among which the organic matter type in the lower sweet spot is mainly type I kerogen, and the organic matter type in the upper sweet spot is mainly type I-II₁ kerogen. Therefore, the organic acid production capacity of source rocks in the upper and lower sweet spots is strong.

5.2. Characteristics of Thermal Evolution Differences in the Sweet Spot

5.2.1. Evidence of Magmatic-Hydrothermal Activity

(1) *Mineralogical evidence.* Some typical hydrothermal mineral assemblages are formed when deep thermal fluids migrate upward to reservoirs. Hydrothermal minerals such as apatite, rutile, fluorite, and calcite vein are observed in the reservoir of Lucaogou Formation in the study area by casting thin sections and scanning electron microscopy (Figures 14(a), 14(b), 14(c), and 14(d)). Veins formed by

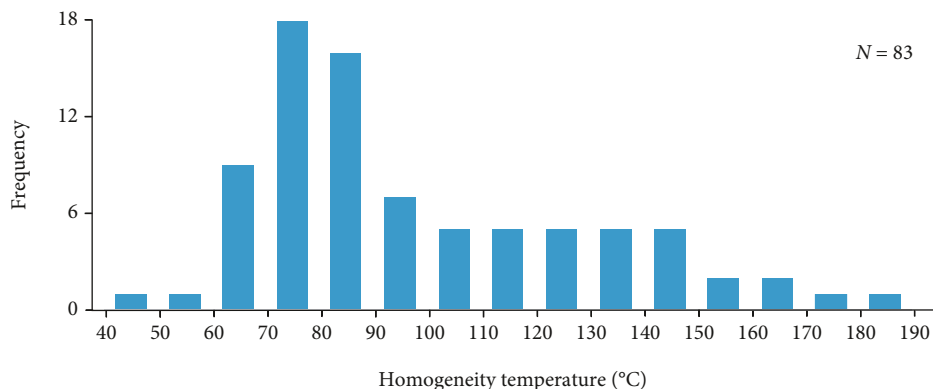


FIGURE 15: Homogeneous temperature distribution characteristics of primary brine inclusions in Lucaogou Formation, Jimsar Sag.

inlaid cryptocrystalline calcite aggregates are developed in reservoir member of Lucaogou Formation, which cut through bedding or distributed along bedding. They have the same characteristics as magmatic-hydrothermal excrete rocks in previous studies, which is evidence of magmatic-hydrothermal activities during diagenesis (Figures 14(c) and 14(d)).

(2) *Evidence of abnormal paleotemperature.* The homogenization temperature of primary saline inclusions captured during mineral crystallization represents the crystallization time. The maximum burial temperature of the sweet spot member of Lucaogou Formation in Jimsar Sag is 140°C (Figure 10(b)). The homogenization temperature of some saline inclusions measured can be as high as 188.3°C (Figure 15), which is significantly higher than the maximum normal formation temperature. This finding indicates the existence of thermal events. The homogenization temperature of primary saline inclusions can be used to determine the magmatic-hydrothermal activity period. When deep hot fluid is rapidly injected into the middle and shallow strata, the temperature of fluid inclusions when captured is higher than that of the stratum at that time. Homogenization temperature spans from 46.2°C to 188.3°C, and the universality of homogenization temperature distribution reflects the difference in mixed crystallization temperature of formation water in hydrothermal fluids of carbonate rocks at different stages. The minimum homogenization temperature of primary brine inclusions is that the hot fluid cools completely to the formation temperature at that time. Burial and thermal evolution histories also determine it as Late Permian (Figure 10(b)). This background is consistent with the Permian magmatic-hydrothermal geological background.

(3) *Evidence of vitrinite reflectance.* Previous researchers found abnormal temperature zones in the upper and lower sweet spots through R_o values of five single wells but without the effect of R_o slope increasing with burial depth (Figures 16(a), 16(b), 16(c), 16(d), and 16(e)). Meanwhile, the content of tuff material and hydrothermal jet material in the sweet spot section is between 60% and 80%, while it is less in the nonsweet spot section, with most layers con-

taining 30% [20]. Therefore, the magmatic-hydrothermal interaction causes the temperature anomalous zones in the upper and lower sweet spots.

5.2.2. *Characteristics of Thermal Evolution Differences.* R_o suggests that the source rocks of Lucaogou Formation in Jimsar Sag are in low maturity stage, and thermal events will accelerate the thermal evolution of source rocks [37, 38]. The thermal energy brought by the upwelling of thermal fluid drives the difference in hydrocarbon source rock maturity between the upper and lower sweet spot sections. The lower sweet spot is more influenced by the upwelling thermal fluid, and the thermal evolution is higher than that of the upper sweet spot section. The Permian of this study area is in the period of intraland rift development, and deep and large fractures are developed. Jurassic system is influenced by Yanshan Movement, which forms the north-south and east-west faults successively. The development of fault zones and fractures also provides channels for magmatic-hydrothermal upwelling. At the same time, the development period of faults and fractures coincides with the hydrocarbon charging period of source rocks; thus, the lower sweet spot is strongly influenced by magmatic-hydrothermal activities [10].

The heat is higher in the area closer to the eruption, and differences in the R_o plane are also observed. The R_o increases from east to west. The vitrinite reflectance values in the sweet spots of wells J36, J174, and J31 are about 1.03, 1, and 0.85, respectively (Figures 16(a), 16(d), and 16(e)), all of which are higher than the corresponding plane demonstration ranges (0.95-1, 0.80-0.85, and 0.75-0.80) (Figure 17(a)). This finding is also due to magmatic-hydrothermal results [21]. The data of 262 from the lower sweet spot of 5 wells in the plane indicate that the effective porosity of the reservoir rock in the sweet spot section of wells J10022, J10025, J305, and J10024 is 6.75%-14.86% (Figure 17(b)). The average porosity of the reservoir rock in the sweet spot section of wells J10005 is 6.70%, which is significantly lower than that of the four other wells. At the same time, J10005 is far from other wells in the magmatic-hydrothermal zone. Magmatic-hydrothermal causes great differences in reservoir properties of the same layer in the study area.

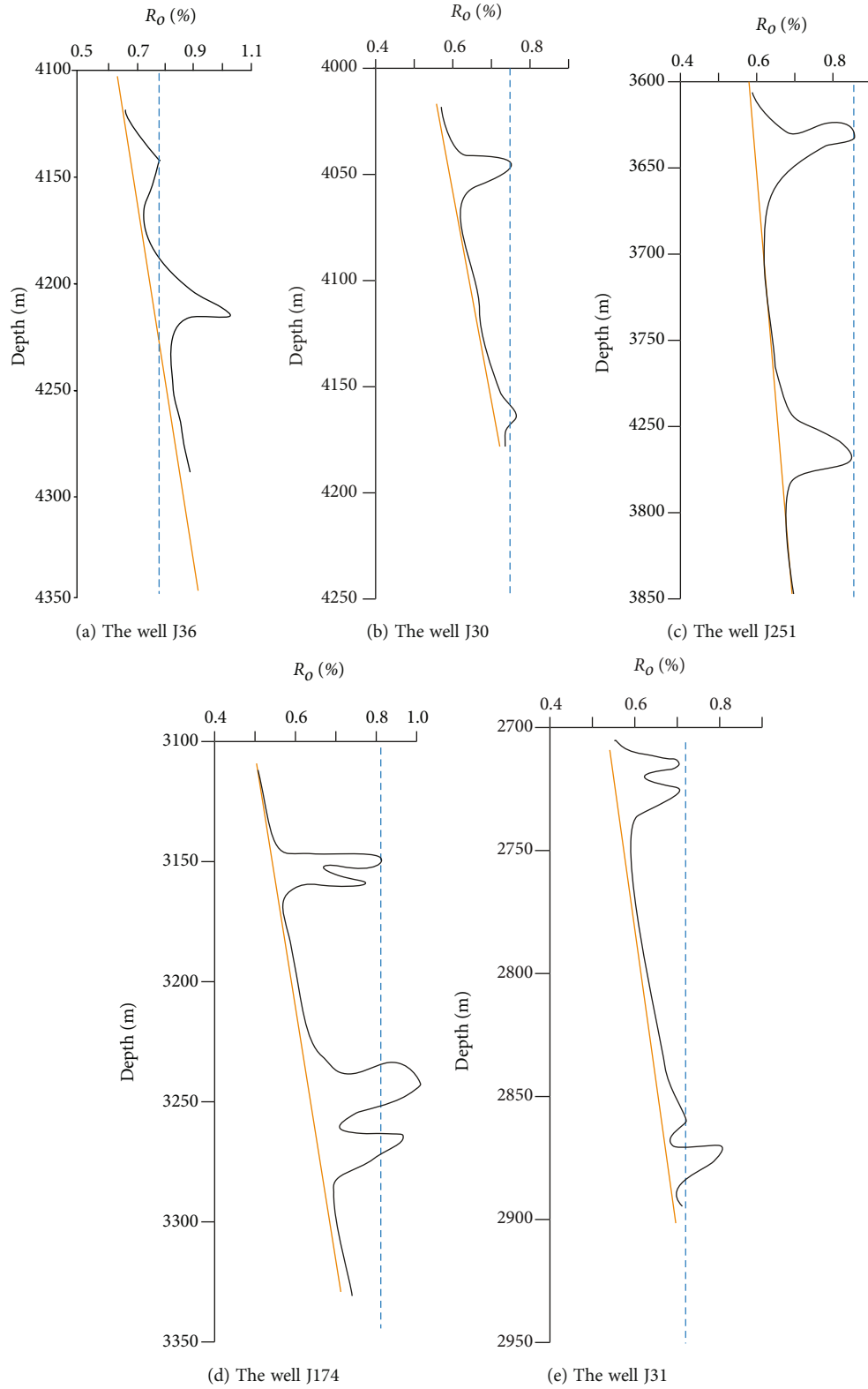
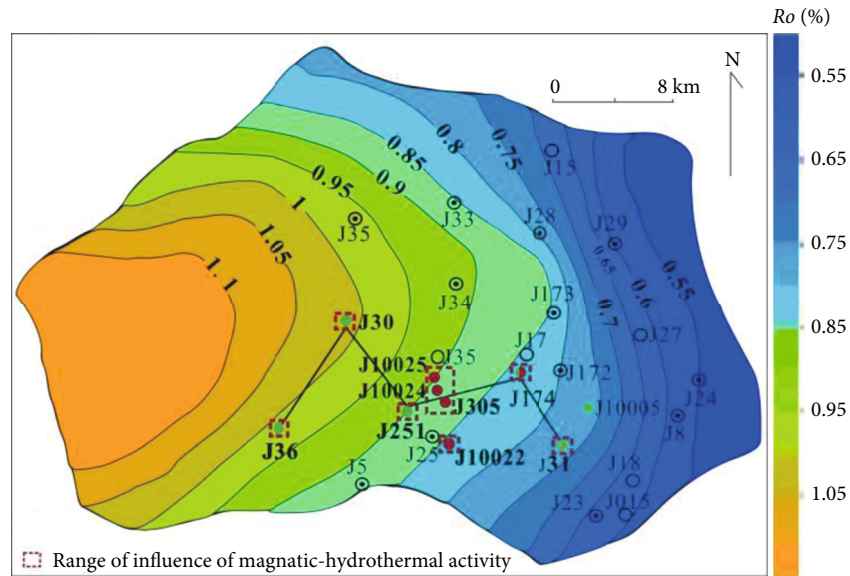
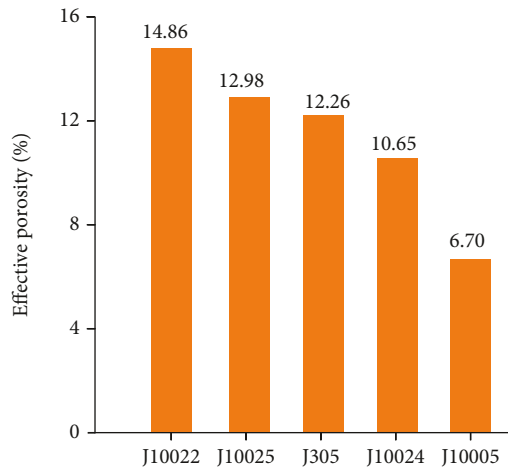


FIGURE 16: R_o -depth evolution map of source rock of Lucaogou Formation in Jimsar Depression (modified from Liu et al., 2019).



(a)



(b)

FIGURE 17: R_o of the whole sweet spot section (modified from Qiu et al., 2016) (a). Effective porosity plane distribution characteristics of the lower sweet spot section of the Jimsar Depression Lucaogou Formation (b).

5.3. Causes of Differences in Acidic Fluids

5.3.1. Differences in Hydrocarbon Generation Potential. The source rocks of the entire sweet spot section of the Lucaogou Formation are developed in a large scale and of good quality. Compared with the source rocks in the upper sweet spot, the lower sweet spot member has a wide distribution in plane, larger thickness in longitudinal direction, larger abundance of organic matter, and better type of organic matter, and most of them are high-quality source rocks with large potential hydrocarbon generation capacity. This feature provides an important source for the different scale production of organic acids during hydrocarbon generation in the upper and lower sweet source rocks.

5.3.2. Differential Thermal Evolutionary Characteristics. The final production of organic acids not only depends on the

preconditions of the size and quality of source rocks but also is closely related to the degree of thermal evolution of source rocks. The homogenization temperature of primary saline inclusions indicates that the magmatic-hydrothermal activity has the characteristics of upwelling in the late stage A of early diagenetic stage (Figure 10(b)). The Late Permian source rocks have not yet entered the large-scale hydrocarbon generation period, and the early release of organic acids from the source rocks is prompted by thermal fluid activity. Previous studies have also shown that hydrothermal deep source rocks are involved in hydrocarbon generation by means of petrology and geochemistry [39]. Owing to the magmatic-hydrothermal upwelling support, the lower sweet spot is more influenced by the rising thermal fluid, the hydrocarbon source rocks in the lower sweet spot have stronger hydrocarbon generation potential, and the scale of organic acid release is much larger than that in the upper

part. Organic acids produce scale differences, which results in significant differences in secondary dissolution pores of feldspar and dolomite in the upper and lower sweet spots. Specifically, strong dissolution in the lower desert section and strong development of secondary dissolution pores are observed.

6. Conclusion

- (1) The upper and lower sweet spots of Lucaogou Formation in Jimsar Sag develop clastic and carbonate rock-soluble components. Reservoir space type and performance development characteristics between the upper and lower sweet spots differ. In particular, the Lucaogou Formation mainly develops dissolution pores, and it mainly exists in the lower sweet spot, while the upper sweet spot has primary intergranular pores; the dissolution intensity of the lower sweet spot is higher than that of the upper sweet spot, and feldspar and dolomite are mainly dissolved. The dissolution effect is the main controlling factor for the obvious difference in the reservoir properties of the upper and lower sweet spots in the study area
- (2) The magmatic-hydrothermal activity causes the difference in the degree of thermal evolution of organic matter in the source rock segments in the upper and lower desert sections of the Lucaogou Formation of the Jimsar Depression. Meanwhile, owing to the larger scale and better quality of source rock development in the lower desert section, the hydrocarbon generation potential is greater, and the scale of producing acidic dissolved fluids is higher than that in the upper desert section. Thus, the dissolution effect between the upper and lower desert sections differs
- (3) The difference in reservoir performance in the same horizon is also caused by magmatic-hydrothermal activity. With the magmatic-hydrothermal vents as the center, the reservoir characteristics in the study area are affected by magmatic-hydrothermal processes to varying degrees in plane. The dissolution effect is more intense when the distance to the magmatic-hydrothermal activity area is closer, which indicates the mechanism of magmatic-hydrothermal action transforming reservoir in plane

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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