Diagenesis Sequence and Hydrocarbon Accumulation Period of the Ordovician Reservoir in Well Tashen-6, Tahe Oilfield, Tarim Basin, NW China

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Cite This: ACS Omega 2022, 7, 29420−29432

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ABSTRACT: The main types of diagenesis, diagenetic minerals and their formation time sequence in the Ordovician ultradep (>/7000 m total depth) carbonate reservoir represented by the Yingshan and Penglaiba Formations (well Tashen-6, Tahe Oilfield, Tarim Basin), are determined by applying microscopic observations, microscopic fluorescence detection, and cathodic luminescence analysis in petrographic thin sections. The distinct periods of reservoir diagenesis and hydrocarbon-related events are determined by analyzing the development characteristics of hydrocarbon inclusions and their relationship with the host minerals. The charging periods of hydrocarbon inclusions are identified by constraining the homogenization temperatures of inclusions. The obtained results indicate that the Ordovician Yingshan and Penglaiba formations have experienced at least three periods of hydrocarbon charging and one period of structural transformation. Their relative time sequence relationship with diagenesis processes is as follows: The limestone dissolution of the Yingshan Formation developed initially, and the first period of hydrocarbon charging occurred (during the late Caledonian). The second period of hydrocarbon charging occurred due to the continuous modification influence of dissolution (late Hercynian−early Yanshanian). The limestones of the Penglaiba Formation were exposed to strong tectonism during the second period of hydrocarbon charging in the Yingshan Formation; thus, intralayer microfractures were formed. Additionally, the first period of hydrocarbon charging in the Penglaiba Formation occurred together with the dolomite reservoir (late Hercynian−early Yanshanian). During the subsequent period, dissolution occurred again due to the continuous increase in burial depth. The third period of hydrocarbon charging developed concurrently with the early fractures (late Himalayan). Finally, the unceasing deepening of the strata accompanied by tectonic activity led to the early intergranular dissolution pores to be cut by late microfractures, which caused the crude oil to convert into bitumen through secondary modifications.

1. INTRODUCTION

Analysis of the hydrocarbon accumulation period is one of the key problems in understanding oil and gas reservoirs and even hydrocarbon-bearing systems. In the case of marine carbonate reservoirs under ancient complex superimposed petroliferous basins, the determination of its time is solid support for the reconstruction of the hydrocarbon accumulation process and the distribution law of oil and gas reservoirs. Additionally, it is of great importance for geological research, exploration, and development of oil and gas reservoirs.1,2 With the progress of knowledge in subjects such as petroleum geology, geochemistry, and geophysics, accompanied by the continuous improvement of technical equipment, researchers can determine hydrocarbon migration and accumulation periods of petroliferous basins by using methods such as dating of diagenetic mineral, geochemical analysis of reservoirs, dating by radioidote, and fluid-inclusion analysis. For the dating method by diagenetic mineral,3,4 the hydrocarbon accumu-
based on the geochemical characteristics of reservoirs and the understanding of the causes that lead to reservoir heterogeneity, which is characterized by the heterogeneity of hydrocarbon fluids in oil and gas reservoirs defined by different thermal maturities. This represents an important reflection of the accumulation or charging history if the relationship between the reservoir heterogeneity and the accumulation period or the charging period, charging direction, and hydrocarbon source kitchen are studied. The shortcoming of this method is that it needs a hydrocarbon generation and discharge history of the corresponding source rock as a reference, and therefore only an estimative accumulation time can be given. The radiometric dating method is used to obtain the accurate age of hydrocarbon accumulation by measuring the isotopic composition of U−Pb, Pb−Pb, Re−Os, Rb−Sr, and Sm−Nd in bitumen, kerogen, and crude oil. However, in most cases, the obtained ages represent the maximum depositional age (MDA) and are usually older than the true depositional age (TDA). For the fluid inclusion analysis method, the temperature of hydrocarbon accumulation is mainly determined on the basis of the trapping temperature of hydrocarbon inclusions. Afterward, quantitative analysis of hydrocarbon accumulation time and period is performed in combination with additional data such as basin burial history and thermal evolution history. At this moment, it represents the most popular and effective accumulation analysis method. However, since the history of hydrocarbon accumulation in complex superimposed basins is characterized by “multisource” mixing and “multiperiod” charging, there are multiple solutions for determining the accumulation time and period by including the homogenization temperature of inclusions onto the burial history and thermal evolution history. Currently, the diagenetic sequence of the host minerals can be determined, and the validity of the inclusion data can be affirmed on the basis of homogenization temperature tests of inclusions, and petrographic analyses of inclusions. That is, two-phase (gas−liquid) aqueous inclusions are symbiotic with hydrocarbon inclusions. Thus, a reasonable explanation for hydrocarbon accumulation and migration can be given by analyzing the mutual relationship between diagenesis and hydrocarbon charging, while the multiplicity of solutions in the experiment results can be avoided.

Oil and gas exploration in China has also shifted to deep and ultradeep areas. The Tarim Basin is a typical multicycle superimposed composite basin. Influenced by multiperiod tectonic vertical movements, the Ordovician oil and gas reservoir is characterized by multiperiod and multisource hydrocarbon generation and accumulation. Its complicated development history has always received attention from national and foreign researchers. The ultradeep oil and gas fields located under the Kelasu salt, such as the Tabei oilfield with reserves of around several trillion cubic meters under atmospheric conditions located, as well as the Tazhong oilfield with approximately 1 billion tons of condensate gas, have been discovered successively in the past years. The ultradeep layers have become an important objective for future oil and gas exploration in the basin.

The Tahe Oilfield in the Tarim Basin is the first Paleozoic marine oilfield in China. Although oil and gas development is mainly concentrated in the upper strata of the succession, several works have confirmed that the middle and lower strata of the Tahe Oilfield also have great exploration and development potential. Many studies have been carried out on the filling time and stage of the Ordovician oil and gas in the Tahe Oilfield, but due to the multistage tectonic movements and complex diagenesis processes in the basin, scholars have different interpretations; most of them believe that the Tahe Ordovician oil and gas reservoirs experienced four main accumulation periods: late Caledonian, late Hercynian, Yanshanian−early Himalayan, and late Himalayan. Chen et al. combined the early Yanshanian−Himalayan period and the late Himalayan period into the first Yanshanian−Himalayan period by employing the analytic methods of crude oil and oil inclusion molecular geochemistry single fluid inclusion micro-spectrofluorimetric

![Figure 1.](http://pubs.acs.org/doi/10.1021/acsomega.2c03737)
and thermal maturity assessment, and microthermometry. Lyu et al. divided it into three periods on the basis of the study of the Ordovician karstic reservoir rock, oil distribution, and oil charge epoch and with consideration of the related study of structure and trap: the late Caledonian—early Hercynian period (early hydrocarbon accumulation and transformation), the late Hercynian period (middle hydrocarbon charging and adjustment and transformation), and the late Himalayan period (late hydrocarbon charging and adjustment). A few scholars believed that the main accumulation period was the late Caledonian period and the Himalayan period in total.26

In this work, well Tashen-6 that was drilled in the Tahe Oilfield, Tarim Basin is considered as the research object. The main diagenesis types, diageneric formations and diageneric sequences of the carbonate reservoirs from the Ordovician Yingshan and Penglaiba Formations, are determined by utilizing microscopic observations, microscopic fluorescence detection, and cathodic luminescence analysis for petrographic thin sections. By analyzing the development characteristics of hydrocarbon inclusions in the reservoir rocks and the relationship between the inclusions and the minerals, the relative chronology between reservoir diagenesis and oil and gas events is established. Finally, under the constraint of inclusions’ homogenization temperature, the charging time and the accumulation period of the hydrocarbon inclusions are revealed, to provide theoretical support for understanding the mechanisms of deep and ultradeep hydrocarbon accumulations in the Tahe Oilfield.

2. GEOLOGICAL SETTING

The Tarim Basin is located in the southern part of the Xinjiang Uygur Autonomous Region, NW China, and is considered one of the largest petroleum-bearing basins in the world.27 The main body of the Tahe Oilfield is located at the conjunction between the Shaya Uplift in the northern part of the Tarim Basin, and the southwestern slope of the Akekule Uplift. Its northern boundary is adjacent to the Yakela Fault-Salient, its southern boundary correlates with the Shuntuoguole Low-Uplift and the Manjiaer Depression, its eastern boundary is connected to the Caohu Sag, and its western boundary is linked to the Halahatang Sag (Figure 1a). Currently, the petroleum-bearing surface controlled by the drilled wells is equal to approximately 2400 km², while its Ordovician reservoirs represent one of the most distinctive types of large carbonate reservoirs in China.28,29 Well Tashen-6 penetrated the marine carbonate rocks of the Ordovician Penglaiba Formation and is one of the few ultradeep wells (>7000 m total depth) drilled in the southwestern part of the Tahe Oilfield. The Akekule Uplift is an ancient uplift formed on a pre-Sinian (Ediacaran) crystalline basement, which underwent 5 periods of tectonic evolution, deformation, superposition, and inheritance development (such as early Caledonian, late Caledonian—early Hercynian, middle and late Hercynian, Indosinian—Yanshanian, and Himalayan). The consequences of the multiperiod tectonic activities resulted in the development of complex hydrocarbon accumulation processes with “multiple sources of rocks, multiple stages of accumulation, and mixed readjustment”.24,32

The sedimentary succession for the Ordovician strata of the Tahe Oilfield from bottom to top consists of the following: the lower Penglaiba Formation (O₁p), the middle to lower Yingshan Formation (O₁−y), the middle Yijianfang Formation (O₂y), the upper Qiaerbaha Formation (O₃q), the Liangtage Formation (O₄l), and the Sangtamu Formation (O₅s). The predominant lithology is represented by limestone deposited in an open platform facies. The lithology in the Penglaiba Formation and Sections 3 and 4 is dolomite and dolomitic limestone, and the reservoir rocks experienced various phases of transformation at different degrees (Figure 1b). The main source rock is the slope-continental shelf facies mudstone from the Lower Cambrian Yuertusi Formation.33 The reservoir capacity is dominated by strike-slip fault-related fracture zones, fractures and dissolution pores along the fractures, mostly filled or semifilled with calcite or bitumen. The major strike-slip faults characterized by multiple episodes of tectonic activity cut down through the main source rocks at the bottom margin of the Cambrian succession. Therefore, these faults established connections with the main hydrocarbon source and created essential conditions for vertical migration and accumulation of hydrocarbons. The tight limestone around the fault zones and the thick cap rock represented by the regional mudstone of the upper Ordovician Sangtamu Formation provide reliable conditions for the preservation of oil and gas accumulated in the reservoirs.34

3. SAMPLES AND METHODS

To better understand the ultradeep hydrocarbon accumulation period of the Ordovician sedimentary succession in the Tashen-6 well, preliminary core observations and petrographic analysis were performed on 6 specimens sampled from carbonate fractures and cave fillings of the Ordovician Yingshan and Penglaiba Formations. The samples were grinded until inclusions were identified, and the thin sections were polished on both sides.

Petrographic analysis and oil inclusion detection were carried out with a Nikon Eclipse 80i dual-channel fluorescence-transmission light microscope equipped on a MAYA2000 Pro fiber Optic spectroscopy analyzer. The length of the UV excitation light wave was set between 330 and 380 nm. Microbeam fluorescence spectra and parameters of individual oil inclusions were obtained by using the SpectraSuite software. A scientific DXR 2xi microconfocal laser Raman spectrometer was used to conduct laser Raman analysis on gas inclusions. A CL8200 MKS-2 cathode luminescence instrument was used for cathode-luminescence tests. The experimental parameters were as follows: voltage, 13 kV; current, 250 μA; and vacuum degree, 0.03 mbar. Carbon and oxygen isotope were measured with a DELTA V Advantage SN09017D gas isotope ratio mass spectrometer and took the instrument mass microprobe in the laboratory. The homogenization temperature and the freezing point temperature of the inclusions were measured with a LINKAM THMSG600 geological cooling and heating platform (the measurement accuracy of the homogenization temperature and the freezing point temperature is ±1 °C and ±0.1 °C, respectively). In this work, all analyses were conducted in the Key Laboratory of Exploration Technologies for Oil and Gas Resources, Ministry of Education, Yangtze University, China, where the laboratory temperature was set to 25 °C and the humidity was equal to 45% relative humidity (RH).

4. RESULTS

4.1. Diagenesis and Diagenetic Sequence. Macroscopic core observations, petrographic analysis, and cathodoluminescence observations performed on one sample from the...
Yingshan Formation and five samples from Penglaiba Formation reveal that the predominant lithology of the carbonate reservoir in this section is represented by fine-microcrystalline dolomite and dolomitic limestone. The dolomite samples are characterized by rose-red cathode light (Figure 2d). At the same time, two generations of calcite cements were detected in the microcrystalline dolomite dissolution pores at a depth of 7440.44 m in the Yingshan Formation. The first generation of calcite cements (VC1) displayed a dark cathode light, while the second generation (VC2) showed an orange-yellow cathode light (Figure 2b). Additionally, two generations of calcite cements were identified in the fractures of microcrystalline dolomite at a depth of 7520.00 m in the Penglaiba Formation. The first generation of calcite cements (FC1) displayed a dark cathode light, and the second generation (FC2) showed an orange-yellow cathode light (Figure 2f). Filling calcite in another period characterized by the absence of cathode light was detected in an intergranular dissolution pore of microcrystalline dolomite at a depth of 7532.00 m in the Penglaiba Formation. The filling calcite was cut by an unfilled microfracture (Figure 2h).

The dolomite rocks from the studied sedimentary succession underwent several episodes of multiperiod tectonic activities and different phases of diagenesis, mainly dolomitization (A in Figure 3), dissolution (B1 and B2 in Figure 3), and cementation and filling, compaction and pressure solution, recrystallization, and tectonic fracturing (C in Figure 3). Consequently, tectonic fracturing, dissolution, and dolomitization are key factors for the formation of high-quality reservoirs. The most important diagenesis characteristics are illustrated in Table 1.

Carbon and oxygen isotope analysis performed on the dolomite from the Yingshan Formation indicates that the \( \delta^{13}C_{PDB} \) value is around \(-2.331\)‰, while the \( \delta^{18}O_{PDB} \) value is approximately \(-13.126\)‰. The results for the dolomite from the Penglaiba Formation show that the \( \delta^{13}C_{PDB} \) values range between \(-10.850\)‰ and \(-8.327\)‰, with a mean value of \(-1.748\)‰, while the \( \delta^{18}O_{PDB} \) values vary between \(-10.850\)‰ and \(-8.327\)‰, with a mean value of \(-9.701\)‰. In the case of the fractures filling calcite, the \( \delta^{13}C_{PDB} \) value is around \(-4.614\)‰, and the \( \delta^{18}O_{PDB} \) value is about \(-16.979\)‰ (Figure 4). Generally, the \( \delta^{13}C \) values for normal marine carbonates vary between \(-5.0 \) and \( 5.0\)‰, while the \( \delta^{18}O \) value ranges between \(-6.0 \) and \(-4.0\)‰. The \( \delta^{13}C \) values of the analyzed samples from the Yingshan and Penglaiba Formations are similar to the values of normal marine carbonates, which may be explained by the smaller influence of freshwater such as atmospheric water. The \( \delta^{18}O \) values are more negative in comparison with the normal marine carbonates. The explanation might be that the oxygen isotopes in the pore water do not only undergo isotopic fractionation during
Table 1. Diagenetic Characteristics of Carbonates from the Yingshan and Penglaiba Formations, Well Tashen-6, Tahe Oilfield

| diagenetic type          | diagenetic characteristics                                                                 | developing condition |
|--------------------------|---------------------------------------------------------------------------------------------|----------------------|
| dolomitization           | Dolomite is mostly micrite and retains the structure of original rock.                      | common development   |
| dissolution              | The late deep burial dissolution can be seen in the situation where late diagenetic cements were dissolved or dissolution occurred along the suture line and fracture; palaeoepigenetic dissolution can be seen in the situation where dissolution pores were formed near the paleo-weathering crust. | common development   |
| cementation and filling  | It has generation cementation structure; the first generation is columnar crystal, the second generation is granular crystal, and, overall, granular cementation prevails. | local development    |
| compaction               | There is common development of compaction, and the particles are in linear contact with each other. | common development   |
| recrystallization        | Microcrystalline crystals recrystallized to powder—mesocrystalline crystals.                | local development    |
| tectonic fracturing       | Microfractures fromed by multiperiod tectonic activity, and most of them were filled with calcite. | local development    |

diagenetic but are also affected by freshwater such as atmospheric water. The dolomite layers are stratified to different degrees throughout the entire section of the Penglaiba Formation, indicating that the sedimentary basin might have been situated in a relatively deep water area characterized by weak carbonate platform hydrodynamics during the early Ordovician period.

4.2. Petrographic Characteristics of Fluid Inclusions.
Fluid inclusions represent the original samples of diagenetic and ore-forming fluids that are trapped in crystals or along healed crystal fractures. They are influenced by a variety of physical and chemical factors during the process of mineral crystallization, such as temperature, pressure, and composition that have been retained during fluid trapping. The hydrocarbon inclusions trapped in the strata are direct evidence of hydrocarbon migration and accumulation. Usually, hydrocarbon inclusions develop in the reservoir minerals during hydrocarbon charging.

Petrographic analysis of the Yingshan Formation indicates that the host for a large number of fluorescent oil inclusions, three-phase (bitumen—oil—gas) inclusions and nonfluorescent pure gaseous-phase methane inclusions is represented by dissolution pores filling calcite. At the same time, some black-brown bitumen is observed in the intercrystalline pores. Petrographic analysis of the Penglaiba Formation shows that a large number of fluorescent oil inclusions and weakly fluorescent or nonfluorescent pure gaseous-phase methane inclusions (Figure 6) are widely distributed in fracture-filling calcite and dolomite (Figure 5g–p). Single-phase and multiphase inclusions coexist in the Ordovician reservoir. Single-phase inclusions consist of oil, gas, or water, two-phase inclusions are a mixture between pairs of oil, gas, and water, and multiphase mixtures represent a combination of bitumen, oil, and gas. On the basis of microscopic observations, the following types of hydrocarbon inclusions were identified: (i) single liquid oil inclusions; (ii) two-phase (gas—liquid) oil-gas inclusions; (iii) gas inclusions; (iv) three-phase (bitumen—oil—gas) inclusions; (v) two-phase (gas—liquid) hydrocarbon aqueous inclusions. The sizes of hydrocarbon inclusions range between 3 and 20 μm, while their shape is primarily elliptic, strip, square, and irregular. The elliptic and irregular shapes are the dominant types.

4.3. Fluorescence Spectral Characteristics of Hydrocarbon Inclusions. The fluorescence characteristics of aromatic compounds in petroleum enable hydrocarbon inclusions to display different fluorescence colors under ultraviolet light, which can be used to quickly and effectively distinguish oil-bearing inclusions from ordinary aqueous inclusions. Distinct fluorescence colors (intensities) suggest the compositional difference between the trapped oil inclusions, indicating the thermal evolution degree of hydrocarbons. Specifically, with an increase in the degree of thermal evolution, the fluorescence color changes in the following order: red → orange → yellow → green → blue → colorless.

The oil inclusions identified in the Ordovician reservoir from well Tashen-6 display the following fluorescence colors: orange-yellow, yellow, yellow-green, and blue-green, while yellow-green and blue-green are the prevalent colors (Figure 5b,h,j,n); three-phase (bitumen—oil—gas) inclusions show an orange-yellow fluorescence color (Figure 5d); gas inclusions are weakly fluorescent or nonfluorescent (Figure 5f,l,p); hydrocarbon-bearing aqueous inclusions are nonfluorescent; bitumen is nonfluorescent, but displays a black-brown color under transmitted light (Figure 5b). According to the fluorescence observation results, it can be preliminarily concluded that the area experienced at least four episodes of oil charging with different thermal maturity and one episode of gas charging throughout the geological time. The bitumen compound may have appeared by oxidation degradation in the terminal period of the initial episode of oil and gas reservoir accumulation.

On the basis of the relationship between the main peak wave length ($A_{max}$), the red green entropy (Q) value, and the $Q_{535}$ of the microbeam fluorescence spectrum of oil inclusions (Table 2 and Figure 7), the Ordovician oil inclusions identified...
in the samples from well Tashen-6 can be approximately divided into four episodes: act 1 is oil inclusions that have an orange-yellow fluorescence color ($\lambda_{\text{max}} = 569.9 - 572.1$ nm; $Q = 0.956 - 1.02$; $Q_{F535} = 2.078 - 2.401$), and the accumulated oil is distinguished by low thermal maturity; act 2 is oil inclusions that display a yellow fluorescence color ($\lambda_{\text{max}} = 540.0 - 550.4$ nm; $Q = 0.503 - 0.662$; $Q_{F535} = 1.348 - 1.666$), and the accumulated oil is distinguished by low thermal maturity; act 3 is oil inclusions that show a yellow-green fluorescence color ($\lambda_{\text{max}} = 521.4 - 537.7$ nm; $Q = 0.416 - 0.592$; $Q_{F535} = 1.227 - 1.465$), and the accumulated oil is distinguished by medium and high thermal maturity; act 4 is oil inclusions that have a blue-green

Figure 5. Microscopic fluorescence characteristics of typical hydrocarbon inclusions in the Yingshan and Penglaiba formations, well Tashen-6, Tahe Oilfield. (a–l) TS6-1, O1p, 7440.44 m, yellow fluorescent oil inclusions, orange-yellow fluorescent three-phase (bitumen-oil-gas) inclusions, and nonfluorescent gas inclusions detected in dissolution pores filling calcite; black-brown asphalt observed in the intercrystalline pores (a, c, and e are under transmitted light, and b, d, and f are under UV light). (g–l) TS6-3, O1p, 7520.00 m, blue-green fluorescent oil inclusions, and weakly fluorescent gas inclusions detected in fracture-filling calcite (g, i, and k are under transmitted light, and h, j, and l are under UV light). (m–p) TS6-5, O1p, 7532.00 m, orange-yellow fluorescent oil inclusions and nonfluorescent gas inclusions detected in fine crystalline dolomite (m and o are under transmitted light, and n and p are under UV light).

Figure 6. Laser Raman spectra of gas inclusions in fracture-filling calcite of the Penglaiba Formation, well Tashen-6, Tahe Oilfield. Micrograph shows methane gas inclusions actually measured in calcite by laser Raman spectroscopy. Peaks: 2912.23 cm$^{-1}$, methane specific peak; 1086.48, 713.36, 281.90, and 154.84 cm$^{-1}$, specific peaks for host minerals that contain inclusions (fracture-filling calcite).
fluorescence color ($\lambda_{\text{max}} = 494.9 - 514.1$ nm; $Q = 0.149 - 0.891$; $Q_{\text{SSS}} = 0.632 - 1.270$), and the accumulated oil is characterized by higher thermal maturity.

4.4. Microscopic Temperature Measurements of Fluid Inclusions. Division of the homogenization temperature for hydrocarbon inclusions and their syngenetic aqueous inclusions in reservoirs is an important basis for determining hydrocarbon accumulation periods. Three acts of oil charging and two acts of gas charging were identified in the dissolution pores filling calcite of the Yingshan Formation in well Tashen-6 (Figure 8a and Table 3). For act 1, the homogenization temperature of oil inclusions that show a yellow fluorescence color is between 46.1 and 56.2 °C, with a mean temperature value of 51.2 °C. The homogenization temperature of syngenetic aqueous inclusions ranges between 110.5 and 113.9 °C, with a mean temperature value equal to 112.2 °C and an average salinity of 5.9 wt % NaCl. For act 2, the homogenization temperature of oil inclusions that display a yellow fluorescence color is between 40.8 and 58.9 °C, with a mean temperature equal to 47.5 °C. For act 3, the homogenization temperature of oil inclusions that display a yellow-green fluorescence color is between 57.1 and 65.8 °C, with a mean temperature of 61.5 °C. The homogenization temperature of syngenetic aqueous inclusions ranges between 128.9 and 133.5 °C, with a mean temperature of 131.8 °C and an average salinity of 23.7 wt % NaCl. For act 1 gas inclusions, the homogenization temperature of syngenetic aqueous inclusions varies from 100.7 to 113.7 °C, with a mean temperature equal to 106.4 °C and average salinity equal to 20.9 wt % NaCl. For act 2 gas inclusions, the homogenization temperature of syngenetic aqueous inclusions is between 125.1 and 133.5 °C, with a mean temperature of 130.8 °C and an average salinity of 22.5 wt % NaCl.

Two acts of oil charging and one act of gas charging were detected in the dolomite rocks of the Penglaiba Formation (Figure 8b and Table 3). For act 1, the homogenization temperature of oil inclusions that display an orange-yellow fluorescence color is between 60.7 and 88.9 °C, with a mean temperature equal to 74.8 °C. No syngenetic aqueous inclusions were identified. For act 2, the homogenization temperature of oil inclusions that show a yellow fluorescence color ranges between 93.9 and 108.9 °C, with a mean temperature of 99.9 °C. The homogenization temperature of syngenetic aqueous inclusions varies between 106.2 and 109.1 °C, with a mean temperature of 106.5 °C and an average salinity of 23.8 wt % NaCl. For one act of gas charging, the homogenization temperature of syngenetic aqueous inclusions is between 103.5 and 121.5 °C, with a mean temperature value equal to 110.9 °C and an average salinity value equal to 21.3 wt % NaCl. Two acts of oil accumulation and one act of gas accumulation were detected in fracture filling calcite. For act 1, the homogenization temperature of oil inclusions that display a yellow fluorescence color is between 46.6 and 61.8 °C, with a mean temperature of 52.0 °C. The homogenization temperature of syngenetic aqueous inclusions ranges between 101.5 and 109.1 °C, with a mean temperature of 104.8 °C and an average salinity of 4.6 wt % NaCl. For act 2, the homogenization temperature of oil inclusions that show a blue-green fluorescence color has high values (>180 °C), which may have been influenced. The homogenization temperature of syngenetic aqueous inclusions is between 97.7 and 108.5 °C, with a mean temperature value equal to

| SN | depth (m) | formation | host mineral | $\lambda_{\text{max}}$ (nm) | Q | $Q_{\text{SSS}}$ | fluorescence color | act |
|----|----------|-----------|-------------|----------------|---|----------------|------------------|-----|
| TS6-1 | 7440.44 | O$_{\text{1,2,p}}$ | dissolution pores filling calcite | 569.9 | 0.956 | 2.078 | orange-yellow | 1 |
| TS6-1 | 7440.44 | O$_{\text{1,2,p}}$ | dissolution pores filling calcite | 544.5 | 0.598 | 1.418 | yellow | 2 |
| TS6-1 | 7440.44 | O$_{\text{1,2,p}}$ | dissolution pores filling calcite | 540.0 | 0.662 | 1.644 | yellow | 2 |
| TS6-1 | 7440.44 | O$_{\text{1,2,p}}$ | dissolution pores filling calcite | 530.5 | 0.592 | 1.465 | yellow-green | 3 |
| TS6-1 | 7440.44 | O$_{\text{1,2,p}}$ | dissolution pores filling calcite | 521.4 | 0.540 | 1.396 | yellow-green | 3 |
| TS6-2 | 7518.70 | O$_{\text{1,2,p}}$ | dolomite | 549.5 | 0.624 | 1.690 | yellow | 2 |
| TS6-2 | 7518.70 | O$_{\text{1,2,p}}$ | dolomite | 545.4 | 0.617 | 1.628 | yellow | 2 |
| TS6-2 | 7518.70 | O$_{\text{1,2,p}}$ | dolomite | 523.2 | 0.421 | 1.239 | yellow-green | 3 |
| TS6-2 | 7518.70 | O$_{\text{1,2,p}}$ | dolomite | 508.2 | 0.442 | 1.231 | blue-green | 4 |
| TS6-3 | 7520.00 | O$_{\text{1,2,p}}$ | dolomite | 545.0 | 0.538 | 1.433 | yellow | 2 |
| TS6-3 | 7520.00 | O$_{\text{1,2,p}}$ | dolomite | 522.7 | 0.416 | 1.227 | yellow-green | 3 |
| TS6-3 | 7520.00 | O$_{\text{1,2,p}}$ | dolomite | 513.6 | 0.342 | 1.015 | blue-green | 4 |
| TS6-3 | 7520.00 | O$_{\text{1,2,p}}$ | fracture-filling calcite | 509.5 | 0.891 | 1.044 | blue-green | 4 |
| TS6-3 | 7520.00 | O$_{\text{1,2,p}}$ | fracture-filling calcite | 508.6 | 0.234 | 0.852 | blue-green | 4 |
| TS6-4 | 7526.00 | O$_{\text{1,2,p}}$ | dolomite | 548.2 | 0.503 | 1.348 | yellow | 2 |
| TS6-5 | 7532.00 | O$_{\text{1,2,p}}$ | dolomite | 572.1 | 1.027 | 2.401 | orange-yellow | 1 |
| TS6-5 | 7532.00 | O$_{\text{1,2,p}}$ | dolomite | 500.4 | 0.633 | 1.666 | yellow | 2 |
| TS6-5 | 7532.00 | O$_{\text{1,2,p}}$ | dolomite | 537.7 | 0.467 | 1.270 | yellow-green | 3 |
| TS6-5 | 7532.00 | O$_{\text{1,2,p}}$ | dolomite | 514.1 | 0.359 | 1.040 | blue-green | 4 |
| TS6-5 | 7532.00 | O$_{\text{1,2,p}}$ | dolomite | 499.1 | 0.149 | 0.632 | blue-green | 4 |
| TS6-6 | 7691.00 | O$_{\text{1,2,p}}$ | dolomite | 526.4 | 0.483 | 1.425 | yellow-green | 3 |

* $\lambda_{\text{max}}$ main peak wavelength; Q, red green entropy.
102.8 °C and an average salinity of 13.4 wt % NaCl. For the single act of gas accumulation, the homogenization temperature of syngenetic aqueous inclusions ranges between 147.5 and 160.9 °C, with a mean temperature of 154.2 °C and an average salinity of 21.5 wt % NaCl. One act of gas accumulation was detected in early dissolution pores filling calcite. For gas inclusions, the homogenization temperature of syngenetic aqueous inclusions varies between 147.7 and 154.1 °C, with a mean temperature of 150.4 °C and an average salinity of 23.3 wt % NaCl.

5. DISCUSSION

5.1. Tectonic Evolution Characteristics and Hydrocarbon Accumulation Process. The Akekule area has experienced multistage tectonic movement and transformation events that played an important role in controlling the structural characteristics of the Tahe Oilfield, as well as hydrocarbon migration and accumulation. Generally, the main tectonic movements of Caledonian, early Hercynian, and late Hercynian ages controlled the development of reservoir space and the channel and direction of hydrocarbon migration, while the Indosinan–Yanshanian and late Himalayan were important periods for oil and gas refilling, adjustment and finalization. That is, the occasional tectonic movements and weathering and denudation during the middle Caledonian provided oil and gas reservoir space and were dominated by karst fracture holes or karst caves in the Tahe area. The strong tectonic uplift during the early Hercynian also provided large-scale accumulation space for hydrocarbons. The late Hercynian tectonic movement continued to provide a favorable location for a large-scale accumulation of oil and gas. The development of faults in the Indosinan–Yanshanian had a certain impact on reservoir transformation and played an important role in guiding the vertical migration of hydrocarbons. The early Himalayan faulting had an important influence on the migration and adjustment of the secondary reservoirs in the upper Ordovician siliciclastic rocks.

5.2. Coupling Relationship between Diagenetic Evolution and Hydrocarbon Charging. As the basis to constrain the fluid charging time, the diagenetic sequence of fluid inclusion host minerals can ensure the reliability of analysis results of hydrocarbon accumulation periods. According to petrographic analysis, the hydrocarbon inclusions trapped in the Yingshan and Penglaiba formations from well Tashen-6 primarily show distinct distribution patterns: distribution in clusters, random distribution, and...
isolated distribution. Fluid inclusions distributed in clusters may be protogenetic or secondary since they are controlled by inconspicuous microfractures. When they are of secondary origin, they can be considered as the same fluid inclusion assemblage (FIA). Fluid inclusions with a random and isolated distribution may be either protogenetic or secondary, but their genesis and the reliability of microthermometry data are difficult to interpret.

On the basis of the tectonic evolution characteristics and hydrocarbon accumulation process in Akekule area and Tahe areas, the relationship between the diagenetic sequence and the hydrocarbon charging of the Ordovician Yingshan and Penglaiba Formations from well Tashen-6 was reconstructed. The dissolution of limestone in the Yingshan Formation occurred earlier, and the dissolved pores were filled with a significant amount of calcite minerals. Simultaneously, yellow fluorescent oil inclusions were captured in the calcite (the homogeneous temperature of syngenetic aqueous oil inclusions is between 74.7 and 86.7 °C), which was the first phase of hydrocarbon charging. In the subsequent phase, it continued to be affected by dissolution and transformation, and captured orange-yellow, yellow, and yellow-green fluorescent oil inclusions and gas inclusions in the calcite minerals (the homogeneous temperature of syngenetic aqueous oil inclusions and gas inclusions ranges between 100.7 and 135.5 °C), which was the second phase of hydrocarbon charging (Figure 9a). The limestone of the Penglaiba Formation was subjected to strong tectonic processes during the second phase of hydrocarbon charging in the Yingshan Formation, which caused the formation of microfractures in the formation. The majority of microfractures were filled with calcite, and afterward yellow and blue-green fluorescent oil inclusions were captured inside the calcite. At the same time, orange-yellow and yellow fluorescent oil inclusions and gas inclusions were captured in dolomite. Oil inclusions captured in fracture-packed calcite and oil and gas inclusions captured in dolomite were generated in the same period (the homogeneous temperature of syngenetic aqueous oil inclusions and gas inclusions varies between 103.5 and 121.5 °C), all of which belong to the second phase of hydrocarbon charging. In the following stage, with the continuous increase in burial depth, the limestone reservoir went through dissolution processes again and a large amount of calcite was filled in the intercrystalline dissolved pores. Gas inclusions were simultaneously captured in the secondary calcite minerals, but also in the late dissolved pores and in the early fractures filled with calcite (the homogeneous temperature of syngenetic aqueous of gas inclusions is between 147.5 and 160.9 °C). This represents the third phase of hydrocarbon charging. Finally, as deep burial and tectonic activity continued to strengthen, early intergranular dissolved pores were cut by late microfractures. Consequently, crude oil was oxidized and degraded into bitumen in the fractures by secondary transformation, forming bitumen-filled fractures (Figure 9b).

### 5.3. Determination of Hydrocarbon Accumulation Period and Time

By analyzing the microscopic characteristics, the spectral characteristics, and the temperatures of the inclusions and by combining the coupling relationship between the diagenetic evolution and the hydrocarbon accumulation, the hydrocarbon charging episodes of the Ordovician Yingshan

| formation | host mineral (occurrence) | act | oil inclusions | syngenetic aqueous of oil inclusions | syngenetic aqueous of gas inclusions |
|-----------|---------------------------|-----|----------------|---------------------------------------|--------------------------------------|
| O₁₋₂y     | dissolution pores filling calcite | act 1 | 46.1−56.2 | 110.5−113.9 | 100.7−113.7 |
|           |                           | act 2 | 40.8−58.9 | 74.7−86.7; 114.9−129.3 | 125.1−135.5 |
|           |                           | act 3 | 57.1−65.8 | 128.9−133.5 |
| O₂p       | dolomite                  | act 1 | 60.7−88.9 | 103.5−121.5 |
|           |                           | act 2 | 93.9−108.9 | 106.2−109.1 |
|           | fracture-filling calcite  | act 1 | 46.6−61.8 | 101.5−109.1 |
|           |                           | act 2 | >180 | 97.7−108.5 |
|           | dissolution pores filling calcite | act 3 | |

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**Table 3. Homogeneous Temperature Data of Fluid Inclusions in the Yingshan and Penglaiba Formations, Well Tashen-6, Tahe Oilfield**

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https://doi.org/10.1021/acsomega.2c03737

ACS Omega 2022, 7, 29420–29432
and Penglaiba Formations were identified. In this study, the selected fluid inclusions are secondary FIAs. Additionally, the homogenization temperature of the aqueous inclusions obtained at the same period as the hydrocarbon inclusions in each episode is regarded as the lowest temperature of the paleofluid at the time of capture and is projected on the burial and thermal history diagram. On the basis of the evolution history map, the charging age and accumulation period of the Ordovician Yingshan and Penglaiba Formations in well Tashen-6 were determined (Figure 10).

The results indicate that the Ordovician Yingshan and Penglaiba Formations are characterized by four episodes of two-stage oil and two-stage natural gas charging, as well as a one-stage transformation, which can be divided into three phases of accumulation: the first phase occurred in the late Caledonian (442.3–438.2 Ma) and consisted of an early episode of low-maturity oil charging; the second phase occurred during the late Hercynian–early Yanshanian (268.2–109.2 Ma) and was predominantly characterized by an episode of oil with medium–high thermal maturity and a natural gas episode charging; the third phase occurred in the late Himalayan (19.4–13.6 Ma) and comprised the late phase of natural gas charging. Among them, the second phase of hydrocarbon charging had a large scale as well as a long time span, so the late Hercynian–early Yanshanian represents the most important accumulation period in this region.

6. CONCLUSIONS
(1) The Ordovician Yingshan and Penglaiba Formations carbonate reservoirs, well Tashen-6 of the Tahe Oilfield, primarily underwent diagenesis processes such as dolomitization, dissolution, cementation and filling, compaction and compression solution, recrystallization, and structural rupture. The relationship between the diagenetic sequence and the hydrocarbon charging is as follows: the limestone strata of the Yingshan Formation were dissolved in the early stage; the dissolved pores were filled with a significant amount of calcite; oil inclusions were captured in the calcite; and the first phase of oil charging occurred, which was followed by dissolution processes. Retrofitting, a second phase of hydrocarbon charging occurred which was characterized by hydrocarbon inclusions captured in calcite minerals. The limestone strata of the Penglaiba Formation were subjected to strong tectonic processes concurrently with the second phase of hydrocarbon charging in the Yingshan Formation. This led to the formation of microfractures in the formation, most of them filled with calcite. Subsequently, the oil inclusions were captured in the calcite and the dolomite minerals simultaneously. Hydrocarbon inclusions occurred in the first phase of oil and gas charging. (Figure 9.)

Figure 9. Schematic diagram of hydrocarbon inclusion capture in different diagenetic stages of the (a) Yingshan Formation and (b) Penglaiba Formation, well Tashen-6, Tahe Oilfield.
charging (both in the second phase of accumulation); afterward the burial depth continued to increase, the limestone reservoir underwent dissolution processes again, and a large amount of calcite was filled in the intercrystalline dissolved pores. Gas inclusions were captured in the calcite filled with late dissolved pores and calcite filled with early fractures. When the third phase of gas filling occurred, the increase of burial depth and tectonic activity continued, early intergranular dissolved pores were cut by late microfractures, and the secondary transformation of crude oil into bitumen occurred, which caused the appearance of bitumen filling joints.

(2) The ultradelic layers of the Ordovician Yingshan and Penglaiba Formations, well Tashen-6, Tahe Oilfield, indicate multistage charging and multistage discontinuous accumulation. There are three main hydrocarbon charging periods: late Caledonian is the first period (442.3–438.2 Ma), late Hercynian—early Yanshanian is the second period (268.2–109.2 Ma), and late Himalayan is the third period (19.4–13.6 Ma). The first phase is characterized by the charging of early oil with low thermal maturity. The charging of oil with high thermal maturity predominantly occurred during the late Hercynian—early Yanshanian. Gas-related activities primarily developed in the late Hercynian—early Yanshanian and the terminal late Himalayan during the same time span with high mature oil filling. The late Hercynian—early Yanshanian represented the most important accumulation period in this region.

(3) The Ordovician in the Tahe area has the characteristics of multistage accumulation and multistage adjustment. The main tectonic movements of the Caledonian, early Hercynian, and late Hercynian periods controlled the development of the oil and gas reservoir space, the channel, and the direction of oil and gas migration. The Indosinian—Yanshanian and late Himalayan were important periods for oil and gas refilling, adjustment, and finalization.

Figure 10. Hydrocarbon burial and thermal history and homogeneous temperature projection of the Yingshan and Penglaiba Formations, well Tashen-6, Tahe Oilfield.
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Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
This work was funded by the China Science and Technology Major Project (No. 2017ZX05008-006-005-002), the Construction of Accumulation Model for Typical Deep Oil and Gas Enrichment Areas and Research on Key Parameters of Resource Evaluation. We also thank the editors and anonymous reviewers for their constructive and helpful comments.

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