Coupling relationship between reservoir diagenesis and hydrocarbon accumulation in Lower Cretaceous Yingcheng Formation of Dongling, Changling fault depression, Songliao Basin, Northeast China

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ABSTRACT

The Lower Cretaceous Yingcheng Formation in the southern Songliao Basin is the typical tight oil sandstone in China. In order to better predict the petrophysical properties of the tight sandstone reservoirs in the Lower Cretaceous Yingcheng Formation, Songliao Basin, Northeast China, the diagenesis and porosity evolution was investigated using a suite of petrographic and geochemical techniques including thin section analysis, scanning electron microscopy, mercury intrusion and fluid inclusion analysis, on a set of selected tight sandstone samples. Combined with the histories of burial evolution, organic matter thermal evolution and hydrocarbon charge, the matching relationship between reservoir porosity evolution and hydrocarbon accumulation history is analyzed. The result showed that the tight sandstone reservoirs characterized of being controlled by deposition, predominated by compaction, improved by dissolution and enhanced by cementation. The hydrocarbon accumulation period was investigated using a suite of hydrocarbon generation and expulsion history, microfluorescence determination and temperature measurement technology. According to the homogenization temperature of the inclusions and the history of burial evolution, Yingcheng Formation has mainly two phases hydrocarbon accumulation. The first phase of oil and gas is charged before the reservoir is tightened, the oil and gas generated by Shahezi source rocks enter the sand body of Yingcheng Formation, influenced by the carrying capability of sand conducting layer, oil and gas is mainly conducted by the better properties and higher connectivity sand body and enriched in the east, which belongs to the type of densification after hydrocarbon accumulation. The second phase of oil and gas charge after densification, which belongs to the type of densification before the hydrocarbon accumulation.

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1. Introduction

Reservoir quality is considered as the crucial factor for effective and viable tight sandstone oil exploration (Scherer M et al., 1987; McCreesh CA et al., 1991; Hart BS et al., 2006; Zou CN et al., 2013, 2014; Dong T et al., 2014; Wang JJ et al., 2015; Li J et al., 2016). Tight sandstone reservoirs have generally experienced complicated diagenetic alterations, causing reservoirs to become tight progressively during burial and thermal evolution (Heward AP et al., 2000; Chester JS et al., 2004; Jiang ZX et al., 2006; Taylor TR et al., 2010; Liu KY et al., 2013; Liu H et al., 2014; Li H et al., 2016). As one of the most important unconventional hydrocarbon resources, tight sandstone oil is widely distributed in major petroliferous basins, potentially forming large-scale petroleum reserves in China (Luo WJ et al., 2012; Chen DX et al., 2012). Pre-drilling exploration potential prediction of low-porosity and low-permeability reservoirs is of great significance for guiding oil and gas exploration and deployment, and reservoir physical property research is the basis and key for the evaluation of oil and gas exploration potential evaluation. When hydrocarbon source rocks expelled, if the properties of the reservoir are good, the hydrocarbon is charged, and deep reservoirs can be formed if they are not damaged in the later period. The reservoir
properties during the critical period of hydrocarbon accumulation largely determine whether oil and gas can charge on a large scale (Vinchon C et al., 1996; Worden PH et al., 2000; Salman B et al., 2002; Ehrenberg SN et al., 2009; Karim A et al., 2010; Yang RC et al., 2012; Zhang YY et al., 2015; Gao Y et al., 2019). Therefore, it is important to have a detailed understanding to the porosity of the sand body during the hydrocarbon accumulation period (Jiang YL et al., 2003; Ni P et al., 2009; Bao SY et al., 2011; Qu DF et al., 2012; Cao YC et al., 2012; Li H et al., 2016).

The Lower Cretaceous Yingcheng Formation tight sandstone is a prolific oil-producing unit in the southern Songliao Basin. The clastic rocks of the Lower Cretaceous Yingcheng Formation in the Dongling area of Songliao Basin have undergone long-term diagenetic transformation, and the diagenesis is complex and has a strong influence on the porosity evolution (Zhang YX et al., 2012; Li H et al., 2016). Although there are many publications dealing with stratigraphy, sedimentology and hydrocarbon accumulation in the southern Songliao Basin, little attention has been paid to sandstone diagenesis and reservoir quality evaluation (Yang RC et al., 2012; Yu YL et al., 2013; Zou CN et al., 2014).

Understanding quantitative diagenetic processes (including oil emplacement) in sandstones and their impact on reservoir quality are essential to further exploration, appraisal and production of tight sandstone oil within this area.

The objectives of this paper were mainly focused on the coupling relationship between reservoir diagenesis and hydrocarbon accumulation. Reconstruct the diagenetic history of the tight sandstones; restore its pore evolution curve; based on the study of hydrocarbon evolution history of hydrocarbon source rocks, the analyze of the reservoir fluid inclusions, comprehensively determined the hydrocarbon accumulation period. The matching relationship between the evolution history of pore and the history of hydrocarbon accumulation is defined.

2. Geological background

The Songliao Basin is a Jurassic–Neogene lacustrine basin with a dual-structure fault-depression in Northeastern China (Fig. 1). The Dongling area of the Changling fault depression is located in the southern part of the Songliao Basin. It is a large nose-like structure extending from the east to the west.
and extending deep into the depression. The study area is nearly 150 km² and is cut by several faults in the northeast direction, forming a number of lithologic-structural traps (Hu YS and Xin CK, 2010; Yu YL et al., 2013; Hou HS et al., 2018; Li YC et al., 2018) (Fig. 1). Sediments filling the basin comprise the Lower Cretaceous Shahezi (K₁sh), Yingcheng (K₁yc), Doulouku (K₁d) and Quantou (K₁q) formations, the Upper Cretaceous Qingshankou (K₂qn), Yaojia (K₂y), Nenjiang (K₂n), Sifangtai (K₂s) and Mingshui (K₂m) formations, the Paleogene Yian (Ny) Formation, the Neogene Daan (Nd) and Kangtai (Nr) formations, and the Quaternary Pingyuan (Q) Formation. The Cretaceous stratigraphy contains many source rocks and reservoir rocks, which can form different oil and gas accumulations vertically. Previous studies indicated that the stratum is mainly the product of lacustrine facies deposition. During the deposition of the Yingcheng Formation, the lake basin expanded to the maximum, which was a shallow lake-semi-deep lake phase (Li M et al., 2009). The studied section (Fig. 2), that is the Yingcheng Formation, was deposited during the depression period of the tectonic evolution, and mainly consists of delta sandstones and some interbedded mudstones (Li M et al., 2009; Li ST et al., 2017). The exploration confirmed that the Yingcheng Formation is the main oil-bearing stratum of the study area. The effective thickness of the source rocks of the Shahezi Formation is 400 m, the type of organic matter is mainly type II, and the thermal evolution reaches the stage of high-over mature. The study area is divided into two fault blocks, the east fault block mainly produces oil, and the west block mainly produces gas.

3. Databases and methods

The studied samples were obtained from drill cores collected by the China Petroleum & Chemical Corporation in the Dongling sag, where exploration drilling activities started in 2016 and produced economic hydrocarbon flows. Since exploration started, core samples, thin sections, data from SEM and mercury injection tests, petrophysical properties and other information related to the exploration wells became available and were used in this research.

In this study, German Zeiss AXIO Imager D1m digital polarized fluorescence microscope with transmitted white and ultraviolet excitation sources is used to analysis the petrographic. Ultraviolet excitation fluorescence characteristics of inclusions obtained by mercury lamp and violet fluorescent filter. Combined with ZEISS color high-resolution digital cold camera AxioCam HRC (12×10³ pixels), AxioVison four image processing software to form a fluorescence microscopic image system. A large number of experimental work has been carried out by comprehensively utilizing the Linkam THMS G600 cold/hot stage for fluid inclusion temperature measurement. For the content of quartz cement, carbonate cements, primary pores and the feldspar dissolution pores, 20 micrographs each of 76 blue or red epoxy resin-impregnated thin sections were taken using the Zeiss Axioscope A1 APOL digital transmission microscope. Then cements and pores in each micrograph were identified under the microscope and sketched on computer using CorelDRAW software, and the total area of cements and pores in every micrograph was obtained using Image-Pro Plus software. Finally, the percentages of the cements and pores were calculated by taking the average of all values in the 20 micrographs from each thin section.

According to the study objectives and constraints of the collected data, the research samples were taken from 11 wells such as S102, SN187 and SN109 in the Dongling area of

Fig. 2. Characteristics of the Yingcheng Formation reservoirs in Lower Cretaceous in Dongling area. a–classification of sandstone using Folk RL’s (1974) criteria; b–porosity distribution characteristics of the Yingcheng Formation tight sandstone reservoirs; c–permeability distribution characteristics of the Yingcheng Formation tight sandstone reservoirs.
Changling fault depression. The sampling horizon was the Lower Cretaceous Yingcheng Formation (K\textsubscript{1Y}). Fifty core samples from 11 wells were prepared as thick doubly polished thin sections for fluorescent color observation, fluid inclusion petrographic analyses and microthermometric measurements. The microthermometry of fluid inclusions was studied using a petrographic microscope equipped with a Linkam THMSG 600 heating and cooling stage which enables temperatures of phase transitions in the range of −180°C to 500°C. Precision was ± 1°C for the homogenization temperature (Th) and ± 0.1°C for the final ice melting temperature, respectively.

4. Results

4.1. Petrological characteristics of sandstones

4.1.1. Reservoir lithologies

Petrographic investigation of the K\textsubscript{1Y} tight sandstones shows that the detrital mainly composed of feldspar lithic sandstone and lithic sandstone, followed by feldspar sandstone and lithic feldspar sandstone (Fig. 2a). The majority of the detrital quartz grains are monocrystalline. Detrital feldspars in these sandstones are mostly plagioclase and altered K-feldspar. Most of the sandstones in main reservoir intervals generally do not contain much detrital matrix. As a whole, the reservoir properties in the K\textsubscript{1Y} sandstones are quite poor (Fig. 2b). According to the statistical analysis of the physical properties of the Yingcheng Formation, the porosity of the elastic reservoirs in this area is mainly distributed between 8% –13%, with an average of 9%. Horizontal permeability ranges from 0.1 mD to 10 mD, with overall performance is low porosity and low permeability (Fig. 2c).

4.1.2. Diagenetic mineralogy

The K\textsubscript{1Y} tight sandstones have undergone significant diagenetic modification, including compaction, feldspar dissolution, quartz and carbonate cementation, clay mineral alteration and some other minor cementation types. Compaction and cementation are the main causes of densification of the sandstones.

(i) Compaction: Evidence of the compaction of the Yingcheng tight sandstone reservoirs is significant in the study area. Ductile grains such as mica are commonly deformed, the fracture of rigid particles, and the contact types are changed from point contacts and line contacts to concavo-convex contacts or line-concavo-convex contacts with increasing burial depth (Fig. 3a).

(ii) Cementation: The interstitial matter in the tight sandstone reservoirs comprises carbonate cements (Figs. 3b, c), authigenic quartz (Fig. 3d) and clay matrix. Carbonate cements are the most common authigenic minerals in the tight sandstones, which usually fill primary intergranular pores or feldspar dissolution pores.

(iii) Dissolution: Dissolution in the tight sandstone reservoirs mainly occurred in feldspar and unstable rock fragments to form dissolution pores (Figs. 3e, f).

(iv) Metasomatism: In the late stage of clastic rock burial, mineral metasomatism is common. Such as calcite metasomatic feldspar (Fig. 3g) and quartz, the kaolinization of feldspar (Fig. 3h), quartz mixed with illite and smectite (Fig. 3i).

4.2. Fluid inclusion test

4.2.1. Petrographic characteristics of hydrocarbon inclusions

The fluorescent properties of hydrocarbon inclusions relate to the presence of luminescent substances such as aromatic hydrocarbons and polar compounds that are present within organic matter in the inclusions. This means that fluorescence properties can be used to distinguish hydrocarbon inclusions from aqueous inclusions. In particular, the longer thermal histories of hydrocarbon yield more stable and strongly polar fluorescent components. This means that the color and fluorescence properties of hydrocarbon inclusions can be used as an indicator of thermal maturity. The thermal evolution of organic matter from low to high maturity causes a change in the composition of hydrocarbon inclusion types from heavy oil inclusions through medium oil and light oil (or condensate) inclusions to gas inclusions. These variations are coincident with a change in inclusion color from black or brown to tan, yellow, light yellow, and finally grey or colorless, with a further change in fluorescence colors from dark brown to brown, tan, yellow, yellow-green, blue-green, blue-white, and finally blue (Heward AP et al., 2000; Tetsuya T et al., 2008; Liu KY et al., 2013). Abundant hydrocarbon inclusions are present within Yingcheng reservoirs in the study area. These inclusions can be divided into two types based on petrographic characteristics (e.g., mode of occurrence, color, phase stage, and fluorescence properties), reflecting the fact that the study area records two periods of hydrocarbon filling.

Period I inclusions fluoresce yellow-green under ultraviolet light (Figs. 4a–f), which indicates that the organic matter captured by these inclusions is of low thermal maturity and is the product of the early-middle stages of hydrocarbon evolution. They are primary, formed during the early stages of the secondary growth of quartz, and are located along micro-fractures that not cut to secondary growth zones or are located within the inner sides of these growth zones. The homogenization temperature of aqueous inclusions associated with these oil inclusions is 60°C –100°C (Fig. 5b), representing the first stage of lower maturity oil charging.

Period II inclusions fluoresce blue-white under ultraviolet light (Figs. 4g–k), indicating that the organic matter was trapped during the later stages of thermal maturity and are related to the middle to high temperature stages of hydrocarbon generation. These inclusions are widespread and are abundant throughout the Yingcheng reservoirs in the study area. They formed after the secondary growth of quartz, and are located along micro-fractures that cross-cut primary or secondary growth zones within quartz or are located in the carbonate cement. A group of gas inclusions generally do not fluoresce under ultraviolet light (Fig. 4l) was also detected in...
the quartz cracks. The homogenization temperature of the aqueous inclusions associated with the oil inclusions is 110°C–140°C (Fig. 5b), representing the second stage of higher maturity oil charging.

4.2.2. Homogenization temperatures of inclusions

The analyses of fluid inclusion generations and their homogenization temperature measurement peaks can be used to determine the hydrocarbon charging phases and timing. Homogenization temperatures derived from individual generations of multi-periods of hydrocarbon accumulation hold different peak models. Single temperature peak usually stands for the fluid inclusion entrapped at a specific time of hydrocarbon accumulation, while different temperature peaks often indicate diverse hydrocarbon accumulation periods (Lu H et al., 2012; Sun MZ et al., 2016). Combined with the history of reservoir burial, the time of hydrocarbon charging can be determined.

Under the constraints of diagenetic sequence, using the Linkam THMS600 cold/hot stage test the homogenization and freezing temperature of the aqueous inclusions associated with hydrocarbon inclusions. The homogenization temperatures of aqueous inclusions within samples from well S6, SN109, SN187, SN108, and SN115 indicate two periods of hydrocarbon accumulation within the Yingcheng reservoirs of study area (Fig. 5). Period I was associated with oil inclusions that fluoresce yellow-green and homogenize at temperatures of 60°C–90°C. Which the oil inclusions and their associated aqueous inclusions are mainly distributed in the cracks of quartz particles and the overgrowth of quartz. In comparison, period II was associated with light oil (or condensate) inclusions that fluoresce blue-white and homogenize at temperatures of 110°C–150°C. Which the oil inclusions and their associated aqueous inclusions are mainly hosted in the cracks in the quartz, the overgrowth of the quartz particles, and calcite cement. Finally, the homogenization temperature of the aqueous inclusions associated with gas inclusions detected in the cracks in the quartz ranged from 130°C–150°C (Fig. 5b).

The aqueous inclusions associated with the hydrocarbon inclusions represents the salinity properties of the fluid at that time. The formula for calculating the salinity is as follows:

\[
W=1.00+1.78T_m-0.0442T_m^2+0.000557T_m^3
\]

W is salinity (%); Tm is the absolute value of freezing point temperature (°C).

The salinity of aqueous inclusions indicate that the

Fig. 3. Microscopic characteristics in the Lower Cretaceous Yingcheng Formation sandstone reservoirs of Dongling. a–photomicrograph of thin section showing detrital grains close contact; b–photomicrograph of thin section showing quartz overgrowth; c–photomicrograph thin section showing of calcite cement in close contact with detrital grains; d–photomicrograph of thin section showing calcite metasomatism feldspar; e–photomicrograph of thin section showing dolomite cement in close contact with detrital grains; f–photomicrograph of thin section showing quartz overgrowth and related feldspar dissolution; g–photomicrograph of thin section showing feldspar dissolution; h–MAPS minerology image showing feldspar kaolinization; i–MAPS minerology image showing quartz with illite and smectite. CC–carbonate cements; Ca–calcite; Qo–quartz overgrowth; Fl-D–feldspar dissolution; Ka– kaolinization; I/S–illite and smectite.
Fig. 4. Fluid inclusion occurrences of Yingcheng Formation in Dongling area. a–oil inclusions along microfracture in quartz grain, which fluoresce yellow; b–oil inclusions along microfracture in quartz grain, which fluoresce yellow-green; c–oil inclusions along microfracture in quartz grain, which fluoresce yellow-green; d–oil inclusions along microfracture in quartz grain, which fluoresce yellow-green; e–oil inclusions at quartz overgrowth, which fluoresce blue-green; f–oil inclusions at quartz overgrowth, which fluoresce yellow-green; g–oil inclusions in cross-cutting trail, which fluoresce blue-white; h–oil inclusions in cross-cutting trail, which fluoresce blue-white; i–oil inclusions in cross-cutting trail, which fluoresce blue-white; j–oil inclusions in cross-cutting trail, which fluoresce blue-white; k–oil inclusions at calcite cement, which fluoresce blue-white; l–gas inclusions in cross-cutting trail, which have no fluorescence.

Fig. 5. Salinities and homogenized temperatures of the hydrocarbon coeval aqueous inclusions of Yingcheng Formation.
Yingcheng reservoirs records two periods of hydrocarbon filling (Fig. 5a). The first period salinity ranges from 1%–2%, and the second period ranges from 4%–7%.

5. Discussion

5.1. Porosity evolution recovery

5.1.1. Paragenetic sequence of diagenesis

The petrographic sequence of diagenesis for the Lower Cretaceous Yingcheng Formation is reconstructed and illustrated in Fig. 6 by synthesizing the petrographic evidence, mineral reactions associated with cement sources, and the interactions between authigenic minerals (Vinchon C et al., 1996; Zhang YF et al., 2011; Storker MT et al., 2013; Yuan GH et al., 2015; Kong LM et al., 2016).

Based on the diagenesis type, characteristics and diagenetic environment analysis, combined with the burial history (Fig. 7), the diagenetic evolution process and its corresponding time in the study area are determined. At 105 Ma from now, the burial depth is about 800 m. With the first charging of oil, the dissolution of numerous unstable components occurred in the oil-bearing sandstones, such as the dissolution of feldspars. SiO$_2$ formed by dissolution of feldspar is not easy to migrate in acidic fluids, quartz overgrowth is formed near the edge (Feng CJ et al., 2013; Dong T et al., 2014). 94 Ma from now, the burial depth is about 1500 m, a large amount of alkali metal ions is released during the transformation of clay minerals, carbonate cementation occurs, and quartz dissolves. At 87 Ma from now, the burial depth is about 2000 m. The second stage of hydrocarbon filling caused the acid water conditions, and the carbonate cement will dissolve. At 60 Ma from now, the depth of the burial is about 2600 m. Due to the temperature rise, illite is substituted to smectite, which finally forms the pore characteristics seen today (Cao YC et al., 2010; Xi KL et al., 2019; Han H et al., 2019).

5.1.2. Porosity inversion and back stripping

The study on the porosity evolution of sandstones in the geological history was carried out with the help of thin section, but the thin section reflected the visage characteristics of clastic rocks. To obtain the true porosity, the conversion relationship between the true porosity and thin visage porosity should be calculated (Wang YZ et al., 2013; Lü ZX et al., 2018). Based on the previous research results and a large number of oil field examples, the real porosity of samples was obtained by using the core mercury injection data in the research area, the visage characteristics of the sample was obtained by means of microscopy and computer image analysis. After the two are matched, the experimental data is fitted, obtain the relationship between true porosity Y and thin visage porosity X: $Y = 1.6968X + 1.0619$, $R^2=0.9908$.

Select a typical view slice of the SN187 well of Yingcheng Formation in the study area, the influence of each diagenesis on porosity is drawn in an artificial circle (Fig. 8). Image-pro Plus 6.0 software was used to calculate the percentage of each cement and dissolution pore in the overall picture, and to determine the influence of each diagenesis on the thin visage porosity.

According to the diagenetic evolution process, the influence of each diagenesis on the visage characteristics is calculated successively. It was calculated that the dissolution of feldspar increased the thin visage porosity by 2.14% and converted into porosity of 5.46%. Quartz overgrowth the loss of 0.23% of the thin visage porosity, translating into a porosity of 0.82%. Carbonate cement lost 6.20% of the thin visage porosity and converted to a porosity of 11.86%. Quartz dissolution increased the thin visage porosity by 0.08% and converted  to a porosity of 0.29%. Carbonate cement dissolution increased the thin visage porosity by 1.68% and converted to a porosity of 3.72% (Fig. 8).

<table>
<thead>
<tr>
<th>Mark</th>
<th>Ro%</th>
<th>Temperature (°C)</th>
<th>Depth/m</th>
<th>Clay minerals</th>
<th>Dissolution</th>
<th>Porosity%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.5</td>
<td>105</td>
<td>1500</td>
<td>Kaolinite</td>
<td>Quartz</td>
<td>0.25</td>
</tr>
<tr>
<td>B</td>
<td>0.7</td>
<td>115</td>
<td>1800</td>
<td>Smectite</td>
<td>Feldspar</td>
<td>0.25</td>
</tr>
<tr>
<td>A1</td>
<td>1.3</td>
<td>135</td>
<td>2800</td>
<td>Illite</td>
<td>Carbonate</td>
<td>0.25</td>
</tr>
<tr>
<td>A2</td>
<td>2</td>
<td>165</td>
<td>3700</td>
<td>Chlorite</td>
<td>Tephrite</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*Fig. 6. Diagenetic evolution sequence of Dongling area.*
Take the sandstone of Yingcheng Formation of SN187 well as an example, porosity inversion and back stripping according to the diagenetic evolution process. The measured porosity of the core mercury intrusion is 8.17%. Therefore, the inversion stripping porosity at the start of dissolution of carbonate cement is 3.98% ([Today’s porosity (7.70%) minus porosity of carbonate cement dissolution increases (3.72%)]. The inversion stripping porosity at the beginning of carbonate cementation and quartz dissolution was 15.55% ([3.98%] plus porosity of carbonate cementation loss (11.86%) minus porosity of quartz dissolution increased (0.29%)]. The inversion stripping porosity at the beginning of feldspar dissolution and quartz secondary increase is 10.91% ([15.55%] plus porosity of quartz overgrowth loss (0.82%) and minus porosity of feldspar dissolution increased (5.46%)]. In this way, the porosity at the beginning of each diagenesis can be obtained (Table 1).

5.1.3. Compaction calibration

The compaction runs through the entire burial process of the sandstones and plays an important role in the loss of porosity throughout the diagenetic stage. With the progress of diagenesis, the appearance of cement will also inhibit the compaction. The porosity inversion and back stripping does not consider the impact of compaction, so compaction calibration is required (Chalmers GR et al., 2012; Loucks RG et al., 2012; Guo HJ et al., 2014).

According to the evolution law of sandstones properties during compaction (Fig. 9) and its sorting coefficient, the original porosity of the sample and the normal compacted porosity at the beginning of each diagenesis are obtained (Table 1). From this, it is possible to calculate the compaction calibration porosity at the beginning of each diagenetic stage.

The burial depth before the feldspar dissolution is shallow and the cementation is almost negligible, so it can be regarded
as the mechanical compaction stage. The compaction calibration porosity is equal to the normal compacted porosity 18.50%. Compaction calibration porosity before carbonate cementation and dissolution of quartz is 19.04% [normal compacted porosity (14.40%) plus porosity of feldspar dissolution increases (5.46%) minus porosity of quartz overgrowth loss (0.82%)]. After the carbonate cementation, the normal compaction is inhibited, there will be a big error in calculating the compaction correction porosity with the normal compaction porosity. Therefore, the total porosity loss after the cementation can be calculated and then distributed to each diagenesis stage according to a certain ratio. Since the beginning of carbonate cementation, the total porosity loss is 3.49% [compacting calibration porosity before carbonate cementation (19.04%) minus current porosity (7.70%) minus porosity of carbonate cementation loss (11.86%) plus porosity of quartz dissolution increasing (0.29%) plus porosity of carbonate cementation dissolution increases (3.72%)]. According to the normal compacted porosity curve (Fig. 9), the porosity lost from carbonate cementation to now is distributed according to the proportion of 3.2 : 2.6 : 0.9. Then the porosity lost by compaction in carbonate cementation and quartz dissolution stage is 1.67%, the porosity lost by compaction in carbonate dissolution stage is 1.35%, and the porosity lost by compaction in metasomatism stage is 0.47%. Therefore, compaction calibration porosity before carbonate dissolution is 5.80% [compaction calibration porosity before carbonate dissolution].

Table 1. Recovering porosity of sandstone in the depth of SN187 in 2263.7 m of Yingcheng Formation.

<table>
<thead>
<tr>
<th>Time/Ma</th>
<th>Depth/m</th>
<th>The inversion stripping porosity/%</th>
<th>Normal compacted porosity/%</th>
<th>Compaction calibration porosity/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>124</td>
<td>0</td>
<td>35.00</td>
<td>35.00</td>
<td>35.00</td>
</tr>
<tr>
<td>105</td>
<td>800</td>
<td>10.91</td>
<td>18.50</td>
<td>18.50</td>
</tr>
<tr>
<td>94</td>
<td>1500</td>
<td>15.55</td>
<td>14.40</td>
<td>19.04</td>
</tr>
<tr>
<td>87</td>
<td>2000</td>
<td>3.98</td>
<td>11.20</td>
<td>5.80</td>
</tr>
<tr>
<td>60</td>
<td>2600</td>
<td>8.17</td>
<td>8.60</td>
<td>8.17</td>
</tr>
<tr>
<td>0</td>
<td>2480</td>
<td>7.70</td>
<td>7.70</td>
<td>7.70</td>
</tr>
</tbody>
</table>

Fig. 8. The microscopic characteristics of the SN187 in 2263.7 m of Yingcheng Formation.

Fig. 9. The reservoir pore evolution curve of SN187 in 2263.7 m of Yingcheng Formation.
cementation (19.04%) minus porosity of carbonate cementation loss (11.86%) plus porosity of quartz dissolution increase (0.29%) minus porosity of compaction loss (1.67%).

The compaction calibration porosity before metasomatism was 8.17% [compaction calibration porosity before carbonate dissolution (5.8%) plus porosity of carbonate dissolution increased (3.72%) minus porosity of compaction loss (1.35%)]. Today’s compaction calibration porosity is 7.70% [the compaction calibration porosity (8.17%) before compaction minus the porosity of compaction loss (0.47%)] (Table 1).

5.2. Hydrocarbon accumulation periods

5.2.1. Hydrocarbon accumulation period determined by the thermal evolution history of source rocks

When the source rocks begin to generate hydrocarbon and meet the requirement of self-adsorption, the activity of the oil-bearing fluid will occur only after the primary migration of crude oil from source rocks. Hydrocarbon generation time of hydrocarbon source rock represents the earliest time of hydrocarbon accumulation (Parnell J et al., 2001; Jin XH et al., 2010; Luo JQ et al., 2017; Zhong MS et al., 2019). Therefore, in order to understand the history of oil filling in the study area, it is necessary to determine the hydrocarbon expulsion threshold of the source rock.

The source rock in the Shahezi Formation are the main source rock layers in the Dongling area of the Changling fault depression, the oil and gas in the study area is mainly from the source rocks of the Shahezi Formation (Cui M et al., 2009; Xu CQ et al., 2010; Yu YL et al., 2013). Previous research has simulated the stratigraphic burial history and thermal evolution history of study area based on the tectonic denudation by vitrinite reflectance constraint. Well S11 from the hydrocarbon generation center of the Shahezi Formation in study area, respectively (Fig. 1), are selected to reconstruct the hydrocarbon generation and expulsion histories. Experimental test and analysis Ro values are available for constraint condition of the simulation. EASY Ro% method was selected and PetroMod software was used for simulation in combination with the formation data. When the simulation of Ro data is consistent with experimental test Ro, it adopts the simulation curve for the final result (Fig. 10). The modelling results show that the hydrocarbon generation of the source rock in the Shahezi Formations initiated hydrocarbon generation during middle stage of Yingcheng Formation (Ro=0.7%–1.0%). Therefore, the hydrocarbon generation of source rock in the Shahezi Formations reached a high peak before the tectonic uplift and erosion and then hydrocarbon generation stopped due to the tectonic inversion. Until the initial stage of the Quantou Formation, the source rock was deeply buried to reach the secondary hydrocarbon generation condition, and hydrocarbons were produced again. In the

![Fig. 10. Hydrocarbon-generating history of Shahezi source rocks of S11 in Dongling area.](image-url)
middle stage of Quantou Formation, the kerogen gradually changed from oil-based to gas-based. At the beginning of the Nenjiang Formation (84 Ma), the source rocks of the Shahezi Formation reached an over-mature stage ($R_o>2.0\%$), the thermal evolution of the source rocks was too high, and the source rocks were depleted (Zhao HH et al., 2017), the second hydrocarbon generation is completed (Fig. 10). According to the history of thermal evolution and hydrocarbon generation, there are two-stage hydrocarbon generation in the Shahezi Formation. The first hydrocarbon generation period is the middle stage of Yingcheng Formation to the late of Denglouku Formation. The second stage is the initial stage of Quantou Formation to Nenjiang Formation.

5.2.2. Hydrocarbon accumulation period speculated from fluid inclusion analysis

Two groups of samples from Yingcheng reservoir can be divided based on the fluorescence color and mineral orientation. The first group is characterized by yellow-green fluorescence hydrocarbon inclusions distributed along micro-fractures that not cut to secondary growth zones or are located within the inner sides of these growth zones (Figs. 4a–f). The second group are characterized by blue-white fluorescence hydrocarbon inclusions within micro-fractures that cross-cut primary or secondary growth zones within quartz or are located in the carbonate cement (Figs. 4g–l). According to the diagenetic sequence and the relationship between host minerals and inclusions, the first group of fluid inclusions were formed during the early period of the hydrocarbon accumulation, and the second group during the late period of the hydrocarbon accumulation.

The analyses of fluid inclusion generations and their homogenization temperature measurement peaks can be used to determine the hydrocarbon charging phases and timing. Homogenization temperatures derived from individual generations of multi-periods of hydrocarbon accumulation hold different peak models. Single temperature peak usually stands for the fluid inclusion trapped at a specific time of hydrocarbon accumulation, while different temperature peaks often indicate diverse hydrocarbon accumulation periods.

Hydrocarbon accumulation periods can be analyzed based on combination of fluid inclusions, burial history, thermal history and hydrocarbon generation and expulsion history. The homogenization temperature of the first-generation inclusions along quartz microfracture and its overgrowth is 80–90°C, which corresponds to the charging time of 106–100 Ma. The temperature peak of the second-generation inclusions in cross-cutting trail and calcite cement is 110–120°C, indicating the corresponding age being 96–85 Ma during burial and thermal histories (Fig. 11).

5.3. Hydrocarbon accumulation and reservoir quality evolution

There were mainly two stages of hydrocarbon filling in the Yingcheng sandstone reservoirs in the study area according to the analysis of fluid inclusions, one was 112–105 Ma, and the other one was 97–82 Ma. From 106–100 Ma, the sandstone of the Yingcheng Formation is in the A stage of the early diagenesis (Fig. 6), and the porosity decreases with the increase of the burial depth. After the early hydrocarbons filled the reservoirs, they inhibited the carbonate cementation, leading to the preservation of reservoir pore spaces. On the other hand, the hydrocarbons tended to carry a large amount of organic acids into the reservoir during the filling process, promoting the dissolution of feldspar and other unstable
components (Cao YC et al., 2010; Tobin RC et al., 2010; Liu MJ et al., 2014). But due to the development of the overgrowth of quartz, the porosity increases little. At this time, the porosity of the sand body is 18%.

From 94 Ma to 87 Ma, the sandstone of the Yingcheng Formation enters the B stage of the early diagenesis (Fig. 6). During the process of clay mineral transformation, a large amount of alkali metal ions is released, and the formation water becomes alkaline. The cementation causes the porosity to drop sharply. After that, the second hydrocarbon charge occurs. The formation of organic acid turns the formation back into an acidic environment, and then the quartz dissolution increases, sandstone porosity increased slightly, at this time the sandstone porosity was 9.5% (Fig. 12).

During the first stage of hydrocarbon accumulation, the Yingcheng Formation sandstone has not been densified, and the sandstone has good physical properties and connectivity. The hydrocarbon generated in the western depression can be transported along the sandstone to the east fault block of the study area. This stage belongs to the type of densification after hydrocarbon accumulation. In the second stage of hydrocarbon accumulation, as the stratum subsides again, the diagenesis in the reservoir continues, and the cementation leads to reservoir densification. At that time, the source rocks of Shahezi entered a high-maturation stage, and the generated hydrocarbon was significantly affected by the transport

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Fig. 12. Coupling relationship between diagenetic evolution and oil and gas accumulation of Yingcheng Formation in Dongling area.
performance of the sandstone of the Yingcheng Formation. It could not be transported over long distances and formed in the west block of the study area. This stage belongs to the type of densification before the hydrocarbon accumulation. According to the analysis of the abundance of inclusions, the second stage plays an important role in hydrocarbon accumulation. High-physical sandstones near the hydrocarbon-bearing depression zone in the west fault block can be a favorable exploration area for hydrocarbon exploration.

6. Conclusions

(i) The tight sandstone reservoirs of the Yingcheng Formation in the study area have undergone significant diagenetic alterations such as mechanical compaction, feldspar dissolution, quartz cementation, carbonate cementation and clay mineral alteration.

(ii) Hydrocarbon inclusions can be divided into two phases: The first phase of the inclusions is mostly long or irregular, isolated or scattered in the cracks of the quartz particles, with yellow-green fluorescence. The homogenization temperature is distributed at 60°C –90°C, corresponding to the early mature oil charge. The second phase of the inclusions is mostly regular elliptical shape, which is distributed in a beaded shape or distributed in the cracks of the quartz. The individual is generally small, with blue-green to blue-white fluorescence, the homogenization temperature is distributed at 110°C–140°C, corresponding to the higher maturity of the hydrocarbon charge.

(iii) There are two main stages of hydrocarbon accumulation in the Yingcheng Formation in the Dongling area, the first stage is the Middle Dengkuku Formation to the lifting and denudation period (106 –100 Ma). The second stage is the middle of the Quantou Formation to the early stage of the Nenjiang Formation (96–85 Ma).

(iv) There is a certain coupling relationship between diagenetic evolution and hydrocarbon accumulation of the Yingcheng Formation sandstone in the study area. The first phase of hydrocarbon is charged before the reservoir is densified, which belongs to the type of densification after the hydrocarbon accumulation. The second phase of hydrocarbon charge after densification, which belongs to the type of densification before the hydrocarbon accumulation.

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References


Storker MT, Harris BN, Elliott CW, Wampler MJ. 2013. Diagenesis of a


