Analysis of deep gas accumulation conditions of the Upper Paleozoic in the southern Huanghua Depression

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Abstract: Influenced by sedimentary and tectonic factors, the accumulation conditions and models of Permian reservoirs in southern Huanghua Depression are unclear. Based on geochemical data of source rocks and petrophysical property data of reservoirs, by means of seismic interpretation, geochemical testing and profile analysis of typical reservoirs, the accumulation conditions are clarified, and the accumulation model is put forward. The study show that the intensity of secondary hydrocarbon generation is a favorable condition for the formation of gas field. The thrust structural traps in Huanghua Depression were mainly formed in the Indosinian, and anticline traps were mainly developed in the Yanshanian and Himalayan. Several source-reservoir-cap assemblages were developed inside the buried hill. Strong tectonic activity created good migration paths for natural gas, and the matching of trap formation, tectonic activity and hydrocarbon expulsion is the key factor of the accumulation of gas. On this basis, the typical gas accumulation pattern is established.

Key words: accumulation conditions; petrophysical property; evolution of source kitchen; faults: deep buried reservoirs;

1. Introduction

Important discoveries have been made in the exploration of primary oil and gas reservoirs in the Wumaying and Wangguantun buried hills (Liao et al.,2003; Zhou et al.,2017; Zhao et al.,2019). Hydrocarbon generation potential, reservoir characteristics and trap conditions are the key factors for further exploration. Therefore, in recent years, a lot of work has been done on source rocks, reservoirs, hydrocarbon migration and accumulation, etc. On the basis of the previous study, the paper analyzed the gas accumulation conditions of the Permian reservoirs in southern Huanghua Depression and established the gas accumulation model. It provides theoretical support for further exploration and reference for the study of Paleozoic petroleum system in Bohai Bay Basin.

2. Regional geological setting

The Huanghua Depression covers an area of about 1.7×10⁴ km² and located in the north central of Bohai Bay Basin. This paper study the southern Huanghua area, and it is covered by Kongdian Uplift, Chengning Uplift and Cangxian Uplift, and the southernmost part of the study area is Wuqiao Sub-sag (Fig. 1A). The upper Paleozoic is composed from bottom to top of the Benxi, Taiyuan, Shanxi,
Xiashihezi, Shangshihezi, and Shiqianfeng formations, with the main source rocks distributed in the Taiyuan and Shanxi formations (Fig. 1B). Different from other depressions, the coal-measure were well preserved in Huanghua Depression (Fu et al., 2016). In the Permian, braided river and meandering river sediments dominate the entire Bohai Bay Basin, in which the Xiashihezi Formation is the main Permian reservoir with thick and stable distribution of sandstone (Han et al., 2019).

3. Analysis of accumulation conditions

3.1 Potential and thermal evolution of source rocks
During the late Paleozoic, frequent transgression events in North China lead to the widespread distribution of coal-measure (Lin et al., 2015). The source rocks at Taiyuan and Shanxi Formation were main source rocks with more and thicker layer (Fig. 1B). The coal-measure source rocks consist of dark mudstone, carbonaceous mudstone, and coal. The organic matter types of coal-measure are mainly type III, part type II2 and a few type II1. The TOC values of coal is greater than 65%, and the values of carbonaceous mudstone are 8%-20%, while the value of dark mudstone are less than 6%. The content of chloroform bitumen A in the coal, carbonaceous mudstone and the dark mudstone are 0.6%-4.0%, 0%-2% and 0%-2%, respectively. The value of (S1+S2) represents hydrocarbon generation potential, and the value of coal, carbonaceous mudstone and dark mudstone are 60–300 mg/g, 2–200 mg/g and 2.5–6 mg/g, respectively (Yang et al., 2020) (Table 1).

| Lithology                  | Thickness /m | Kerogen type               | TOC | Chloroform bitumen A   | Ro       | S1 + S2/ (mg · g⁻¹) |
|----------------------------|--------------|----------------------------|-----|------------------------|----------|---------------------|
| Coal                       | 15–25        | Mainely type III           | >65%| 0.6%-4.0%, mainly 1.0%-3.0% | 60–300   |
| Carbonaceous mudstone      | 30–60        | with some type II2 and a few II1 | 8%-20%| 0.015%-0.28%       | 2–200    |
| Dark mudstone              | 60–150       | <6%                        |     | 0.5%-3.73%              | 2.5–6    |

The effectiveness of source rocks is reflected by the intensity of hydrocarbon expulsion, the good source rocks provide abundant resources for natural gas migration and accumulation. Yang et al. (2020) studied the hydrocarbon expulsion intensity of source rocks in the southern Huanghua Depression, and
concluded that in the early-middle Jurassic, the source rocks entered the expulsion threshold and had certain hydrocarbon expulsion intensity. The source rocks in the Wumaying area were buried deep, and oil and gas are continued to be expelled in the early Cretaceous. The study area was uplifted and hydrocarbon expulsion stopped in the late Cretaceous. From the late Paleogene to the late Neogene, the strata were greatly settled, and the source rocks continued to discharge large amount of hydrocarbons. At present, the center of source kitchen is located in Wumaying area, with the expulsion intensity exceeding $90 \times 10^8 \text{m}^3$, which is an important material basis for gas accumulation (Fig. 2).

3.2 Traps and reservoirs
Starting from the late Triassic, the entire North China plate was in an NW-SE compressive stress environment due to the Indosinian movement (Fu et al., 2016). The thrust nappe structure in the south of Huanghua began to develop due to the strong compression, and the traps were shaped in Mesozoic. The traps were mainly distributed in Wangguantun and Wumaying areas, and the representative traps were the thrust nappe structural traps in Wumaying area (Fig. 3a). This kind of thrust structure mainly involves the Carboniferous-Permian, and thrust faults rarely cut through Mesozoic. Owing to the strong tensile effect in Mesozoic and Cenozoic, the hanging wall on the east and west sides of the fault edge sank considerably, and the central area far from the fault edge gained a small subsidence range, forming the Wangguantun anticline (Fig. 3b).

![Fig. 3 Main types of traps in study area](image)

The upper Paleozoic reservoirs are mainly composed of sandstone from Taiyuan Formation, Shanxi Formation, Shangshishezi and Xiashihezi Formation, of which Xiashihezi Formation is a high-quality reservoir development section. The reservoir of Taiyuan Formation is dominated by barrier island sandstone and carbonate rock, and the sandstone of barrier island is 30-65 meters thick. The reservoir of Shangshihezi and Xiashihezi Formations are mainly channel sand bodies, with the maximum single layer thickness of 30 meters and the accumulative thickness of 80-180 meters, which are the best reservoir sections in the Upper Paleozoic. The testing data analysis shows that the petrophysical properties of Permian reservoirs almost do not variate with the increase of burial depth (Fig. 4a). Take YG2 well for example, in the deep reservoir with a buried depth of 4,701.56 meters, porosity can still reach 14.2%, among which fracture porosity is 2.0%. Besides, the connected pores account for 93.97% of the total pores. The petrophysical properties of deep reservoirs in southern Huanghua are mainly determined by the following four aspects. First, at the end of the Indosinian, tectonic uplift exposed the reservoir, and weathering and leaching improved the physical properties of the reservoir. Second, the strata had been buried deep for several times, and large amount of organic acids and CO$_2$ were generated from coal-measure, which accelerated the dissolution of feldspar, calcite and other minerals. Third, in the early stage of hydrocarbon accumulation in study area, liquid hydrocarbons were injected into pores (Yang et al., 2020), which inhibited the overgrowth of quartz. Finally, the reservoir experienced the superposition of the Indosinian, Yanshanian and Himalayan movements, which resulted in the development of reservoir fractures. The development of intergranular pores, fractures and dissolution pores in the present reservoirs is caused by the comprehensive influence of various factors (Fig. 4b,c), which ensures that the deep reservoirs in Huanghua Depression still have good physical properties.
Fig. 4 Reservoir physical properties change with depth and reservoir characteristics under microscope

3.3 Source-reservoir-cap assemblages
There are 3 sets of source-reservoir-cap assemblages in the upper Paleozoic (Fig. 1B). High-quality coal-measure source rocks are mainly distributed in Taiyuan formation and Shanxi Formation, and coal-measure are also good sources of gas (Dai et al., 2018). First of all, there are sandstone reservoirs with certain thickness in Shanxi and Taiyuan Formations, and mudstone and coal seam can also become good regional cap, forming the first source-reservoir-cap assemblage. Secondly, the thick sandstone reservoir of the Xiashihezi Formation and the thick mudstone cap of the Shangshihezi Formation constitute the high-quality reservoir-cap assemblage. Finally, the sandstone reservoir of Shangshihezi Formation and mudstone-gypsolyte cap of Shiqianfeng Formation constitute the reservoir-cap assemblage.

3.4 Migration and accumulation of gas
The accumulation model of gas reservoir in the southern Huanghua Depression is Paleozoic source and Paleozoic reservoir, and the coal-measure is high-quality gas source rock (Zhao et al., 2019). The typical seismic profile indicates that the faults are main paths of gas accumulation, and the gas is mainly transported along the vertical direction of fault. The Indosinian thrust structure takes the Ordovician as the slippage layer and cuts upward into the interior of the Carboniferous - Permian (Fig. 5a), which can better connect the coal-measure and the upper Paleozoic reservoir. The Yanshanian and Himalayan extensional faults extend upward for a long distance and can be long distance migration channels for natural gas (Fig. 3b). The upper Paleozoic reservoir is close to the source rock and has good physical properties, which can effectively accumulate natural gas. At the same time, the top surface of the upper Paleozoic was weathered and leached, resulting in the distribution of high-quality reservoirs on the top surface of the buried hill of the Paleozoic, and the unconformity surface could be the migration path (Fig. 5b). Under the condition that the reservoir and the source rocks were connected by faults, the natural gas expelled from the source rock will be efficiently transported to the upper Paleozoic reservoir along the faults and unconformity during the tectonic active period.
4. Accumulation model of gas
The upper Paleozoic reservoir in Huanghua Depression is still an effective reservoir when the buried depth is close to 5000 meters (Fig. 4), which is a favorable factor for natural gas accumulation. The matching of trap forming stage, main gas-generating stage and tectonic active stage is the decisive factor for deep reservoir formation. Taking the Wumaying buried hill as an example, gas accumulation model was established. According to the evolution characteristics of the source rocks, by the end of the Cretaceous, the hydrocarbon expulsion intensity was only $22.77 \times 10^8 \text{m}^3$, and thermal maturity was low, mainly producing liquid hydrocarbons (Yang et al., 2020). At the end of the Cretaceous, the Bohai Bay Basin experienced significant uplift (Fu et al., 2016), and paleo-reservoirs were destructed. Therefore, the scale of gas reservoir depends on the secondary hydrocarbons generation and its matching with the tectonic active period in the study area. At the end of the Paleogene and the Neogene, the hydrocarbon expulsion intensity of the source kitchen reached $78.26 \times 10^8 \text{m}^3$ and $89 \times 10^8 \text{m}^3$ (Fig.2), during which there was large amount of gas generated (Yang et al., 2020). The traps in Wumaying thrust belt were formed in Indosinian and Yanshanian, and the traps were formed earlier than secondary gas generating period. From Paleogene to Neogene, the strata were almost in the stage of continuous deep burial, that is, the oil and gas were continuously generated from source rocks. In the middle late Paleogene and the late Neogene, large amount of gas can be charged into traps along faults during the tectonic active period (Li et al., 2019), thus creating favorable conditions for forming deep gas fields (Fig. 6).

![Accumulation pattern of deep buried gas reservoirs in Wumaying Area](image)

Fig. 6 Accumulation pattern of deep buried gas reservoirs in Wumaying Area

5. Conclusions
Coal-measure source rocks are well preserved and have great potential. The source rocks experienced two hydrocarbon generating processes, the first of which is in the early Cretaceous, and the scale is small and mainly generated liquid hydrocarbon. The second of which is from the middle Paleogene to the present, and the hydrocarbon generation scale is large and is dominated by gas.

The physical properties of the reservoirs did not change significantly with the buried depth, and effective reservoirs were still developed close to 5000 meters. In the study area, there are several sets of source-reservoir-cap assemblages.

Fracture system is important in the accumulation of gas and vertical migration of gas is dominated in study area. In addition, the unconformities of the upper Paleozoic can also be used as the favorable area of natural gas transport and accumulation.

Several types of traps were developed due to multiple tectonic activities, and the trap formation period was earlier than the main period of hydrocarbon expulsion. The matching of main gas-generated period and tectonic active period provided the favorable conditions for forming deep gas fields.
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