Characteristics and petroleum geological significance of high-quality source rock in Gufeng Member of Middle Permian Maokou Formation in northern Sichuan Basin, China

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Abstract. Based on the comprehensive analysis of drilling and outcrop profile data, the stratigraphic boundary between Middle Permian and Upper Permian in northern Sichuan Basin is redefined systematically. It is confirmed that the source rock of carbonaceous and siliceous mudstone is widely developed in the Gufeng Member of Middle Permian Maokou Formation in the northern part of the basin, and its thickness is mainly between 5-40 m. The source rock in the Gufeng Member has large variation scope of TOC, mainly in the range of 0.5%-30%, and the average value of most profiles more than 2.0%. It is a set of high-quality source rock as a whole. Its major organic matter is type II. At present, its thermal maturity changes greatly, and it is in the mature-over mature stage. The deep-water sedimentary environment, strong reduction conditions and high paleo-productivity jointly controlled the development and distribution of high-quality source rock in the Gufeng Member under the background of extensional structure at the end of the Middle Permian. High-quality source rock in the Gufeng Member is of great significance to the exploration of marine conventional natural gas and shale gas in northern Sichuan Basin.

1. Introduction

The Permian was an important period for the development of marine source rocks in the Yangtze region of China, developing source rocks in several formations and members [1-3]. Previous studies generally concluded that the organic-rich source rocks in the upper Yangtze region are mainly developed in the Upper Permian Wujiaoping Formation and the Dalong Formation, while the Middle Permian is mainly carbonate source rocks with low TOC, lacking high-quality source rocks [1-3]; while the Middle Permian Gufeng Formation (Member) in the middle-lower Yangtze region developed high-quality source rocks [4]. In fact, a set of stratum dominated by black thin siliceous and carbonaceous shale was developed above the limestone of the Middle Permian Maokou Formation in several outcrop sections in the northern margin of the upper Yangtze region. Its sedimentary characteristics are similar to the Gufeng Formation in the lower Yangtze region. It was also called the Gufeng Formation [5, 6] or the Gufeng Member of the Maokou Formation [7]. At present, the development and distribution of black rock series in the Gufeng Member of the Maokou Formation in the Sichuan Basin is not clear, and its organic geochemical characteristics and hydrocarbon generation potential are lack of systematic evaluation. By fully applying outcrop and drilling data, based on systematic stratigraphic correlation and sampling analysis, the distribution, geochemical characteristics and development control factors of source rock in the Gufeng Member of the northern part of the basin and its adjacent areas are basically clarified in this paper, and its hydrocarbon generation potential and petroleum geological significance are revealed.
2. Age determination of the Gufeng Member

Several outcrop profiles in the northern part of the Sichuan Basin and its adjacent areas show that a few to tens of meters-thick black thin siliceous and carbonaceous shale strata are developed above the thick limestone of the Middle Permian Maokou Formation, and the grey green bauxite is developed on the top, overlaid by the "Wangpo shale" section of the Upper Permian Wujaping Formation (Fig.1). The siliceous rock belt of the Gufeng Formation (Member) distributed from east to west in the northern margin of South China Block has different corresponding relationships with the Maokou Formation limestone in different areas, becoming younger from east to west. This means that from the early Maokou period to the late Maokou period, the Gufeng Formation in the lower Yangtze area was only equivalent to the limestone in the lower Maokou Formation, and the age was the early Maokou period of the Middle Permian. However, in the northern margin of the Sichuan Basin, it is equivalent to the upper limestone section of the Maokou Formation, and its age was the late Maokou Formation [6,8].

The outcrop profiles show that the contact relationship between the siliceous and carbonaceous mudstone of the Gufeng Member and the limestone of the Maokou Formation is clear, and the contact is continuous deposition and conformity; on most profiles, its contact with the overlying "Wangpo shale" of the Wujaping Formation is parallel unconformity, and performs as continuous deposition and conformable contact in some zones.

On outcrop profiles, the siliceous and carbonaceous mudstone of the Gufeng Member in the Maokou Formation is easily distinguished from the overlying "Wangpo shale" of the Wujaping Formation. However, in drilled wells, the Gufeng member is often mistakenly classified as the "Wangpo shale" section due to their adjacent strata and organic-rich shale with high GR value, and then it is considered that the Middle Permian in the Sichuan Basin is lack of large-scale high-quality source rocks [1,3]. It is difficult to distinguish the "Wangpo shale" and "Gufeng Member" in drilling only by natural gamma ray (GR) curve. However, they were formed in different environments and have obvious differences in mineral and element compositions, and have different response characteristics on uranium (U) and thorium (Th) logging curves. In general, the logging characteristics of the Gufeng Member are high GR, low Th, high U (or high U/K), low neutron porosity and low AC values; while the logging response of the "Wangpo shale" section is characterized by high GR, high Th, low U (or low U/K), high neutron porosity, high DEN and high AC values. According to the difference of well logging responses, the stratigraphic boundary between Middle Permian and Upper Permian in more than 50 wells in northern Sichuan Basin is redefined. The organic-rich mudstone with high GR, high U and low Th at the bottom of the original Wujaping Formation is classified as the Gufeng Member of the Maokou Formation. According to the new stratigraphic division, the Maokou Formation in the north of the Sichuan Basin develops several meters to nearly 100 meters of the Gufeng member (Fig. 2).

Fig. 1 Geochemical comprehensive column of Gufeng Member on Wujiping profiles in northern Sichuan Basin, China
3. Distribution of source rocks in Gufeng Member
Based on the re-identification of strata in the Gufeng Member of key wells and systematic sampling analysis, the thickness of high-quality source rock with TOC > 2.0% in different drilled wells and profiles in northern Sichuan Basin and its adjacent areas was redefined, and its plane distribution was determined. In the study area, the high-quality source rock in the Gufeng Member is generally distributed in NW-SE direction, with a total area of about 11×10^4 km^2; the thickness changes greatly, mainly in the range of 5-40m. It is thicker (usually>10 m) in the belts of Guangyuan-Dazhu, Shizhu-Jianshi, Tongjiang-Xuanhan; it is generally less than 5m in the belt along Kaixian-Liangping. In the vast area to the south of Jiange-Nanbu-Linshui belt, the carbonaceous and siliceous mudstone in the Gufeng Member transforms into limestone in the Maokou Formation, and high-quality source rock is not developed.

4. Characteristics of source rock in Gufeng Member
4.1 Rock and mineralogical characteristics
The lithology of the Gufeng Member is complex, which is often manifested as interbedding siliceous mudstone, siliceous rock, carbonaceous shale and limestone with varying thicknesses, developing horizontal lamina and rhythmic bedding; rich in radiolarians, conodonts, brachiopods, bivalves, crinoid stems and other biological fossils. Mineral composition analysis shows that the source rock in the Gufeng Member is rich in siliceous minerals such as quartz, with quartz content between 5.0%-93.6% (averaging 53.5%), average calcite content of 33.9%, average dolomite content of 9.32%, clay mineral content basically less than 10%, feldspar mineral content less than 2.0%, higher pyrite content with an average of 2.5%. The quartz in the organic-rich siliceous rocks and siliceous mudstones is mainly cryptocrystalline quartz under microscope, and a large number of silicified sponge spicules, radiolarians and foraminifera fossils can be seen, suggesting that their genesis is related to biological processes. The ratio of Al/(Al+Fe+Mn) in siliceous rocks in the Gufeng Member is between 0.3-0.69 (averaging 0.5), also presenting feature of biological origin.

4.2 Organic geochemical characteristics
The Gufeng Member is rich in organic matter. The TOC of 134 analyzed samples ranges from 0.12% to 31.04%, with an average of 4.82%. Hereinto, the average TOC value of 127 samples that reach source rock standard (TOC>0.5%) is 5.08% (Fig.4); 67% of high-quality source rock samples have TOC greater than 2.0%; In most wells and profiles, the average TOC values are more than 2.0%. Generally, the source rock in the Gufeng Member of the study area is characterized by rich organic matter, large variation, and high average value of TOC.
The δ13C value of kerogen in the Gufeng Member is mainly from -25.6‰ to -28.3‰. In organic macerals, the contents of sapropel and exinite are high, with an average content of 29% for the former and 52.4% for the latter; the average content of vitrinite and inertinite is 17.8% and 8.8% respectively. The δ13C value of kerogen and the contents of various organic macerals indicate that the organic matter type of the source rock in the Gufeng Member is better, mainly type II. The vitrinite reflectance (Ro%) varies greatly, ranging from 0.75% to 4.5%. In the northern part of the Sichuan Basin, the source rock of the Gufeng Member reached the threshold of hydrocarbon generation during the early stage of the Early Triassic, and reached the highest maturity during the Middle Cretaceous, then the evolution of hydrocarbon generation was terminated, and now it is in the over-mature stage. In the outcrop area around the basin, because of the early uplift of the strata, it is mainly in the mature-high mature stage.

5. Development environment and main controlling factors of source rock

5.1 Development environment of Gufeng Member

The Zr/Rb value in sedimentary rocks can be used to quantitatively characterize the hydrodynamic changes in the sedimentary period: the larger the Zr/Rb value, the stronger the hydrodynamic changes reflected. Zr/Rb values of the source rock in the Gufeng Member vary little, among which, the Zr/Rb values in the Guangyuan area are in the range of 0.85-1.95 (averaging 1.38) (Fig.1), and that in the Wangcang area is between 1.15-2.95 with an average of 1.86. It shows that the source rock was in a sedimentary environment with relatively stable water energy and weak hydrodynamic force. The Sr content of the source rock of the Guangyuan area is chiefly between 100-600 μg/g; the Rb/K ratio in this area is between 0.0028-0.0042 (Fig.1). The Sr content of the source rock of the Wangcang area is between 31.9-597 μg/g; the Rb/K ratio in this area is between 0.0035-0.0055. According to the Sr content and Rb/K value, the Gufeng Member was generally normal seawater deposition, and part of the period was semi-salinized to salinized environment.

The redox conditions of sedimentary water are one of the key factors for the preservation of organic matter. Parameters such as Th/U, V/(V+Ni), Ni/Co and δU(δU=2U/(U+Th/3)) have good indications for the redox environment of sedimentary water. For the source rock in the Gufeng Member in the northern part of the Sichuan Basin, the Th/U value is extremely low, ranging from 0.04 to 0.63, with an average of only 0.19 (Fig.1 and Fig.3a); the V/(V+Ni) value is between 0.38-0.92 (averaging 0.66); the Ni/Co value is between 6.41-125.71, larger than 15 in most samples, averaging 37.83 (Fig.1 and Fig.3c); the δU value is between 1.65-1.97, with an average of 1.88. The above indexes all show that the carbonaceous and siliceous mudstone in the Gufeng Member was mainly formed in oxygen-poor to anoxic environment, and it was in sulfide anoxic environment in some periods.

Marine paleo-productivity is one of the important parameters for judging sedimentary environment and evaluating source rocks. The contents of some nutrient elements related to biological development, such as P, Cu and Zn, are often used to indicate the level of marine paleo-productivity. For most samples of source rock in the Gufeng Member, their P/Ti values are larger than 1.0 (averaging 3.18) (Fig.1); their Ba_{ss} values are between 9.28-120.90×10^6; their Zn_{ss} values are between 38.40-837.92×10^6; their Cu_{ss} values are between 9.30-88.56×10^6. All the samples have positive Ba_{ss}, Zn_{ss} and Cu_{ss} values (Fig.1, Fig.3d-f). The results of measurement and data analysis of the three nutrient elements (Ba, Zn and Cu) in the source rock samples of the Gufeng Member show that they are obviously autogenous enrichment. In combination with P/Ti value, the marine environment in the Gufeng Member of the study area had a very high paleo-productivity level during the sedimentary period.
5.2 Controlling factors of source rock development

The ideal conditions for the development of high-quality source rocks are high initial productivity and good organic matter preservation conditions (reducing burial environment). There is an obvious negative correlation between the measured TOC and Th/U (Fig. 3b) and an obvious positive correlation with Ni/Co (Fig. 3c), indicating that the stronger the reducibility of the sedimentary environment, the more conducive it is to the preservation of organic matter. In addition, there is also a good positive correlation between TOC and Ba_{xs} and Zn_{xs}, which reflect paleo-productivity (Fig. 3d-e), indicating that organic matter was more enriched in sediments during the period of high paleo-productivity. Marine paleo-productivity and redox conditions are both controlled by tectonic and sedimentary backgrounds. The nature of the Late Paleozoic basins in southern China was generally characterized by obvious extensional characteristics, with two types of rift basins, namely, plate margin rift and intra-plate rift. The northern Sichuan Basin was located in the transition zone from the Middle-Upper Yangtze craton basins to the South Qinling rift basins at the deposit end of the Maokou Formation. Under the action of basement faults or synsedimentary faults, a series of deep-water intra-platform rifts were formed. The intra-platform rift basins had deeper sedimentary water body than the carbonate platforms, with weaker hydrodynamic conditions and stronger reducibility, which is favorable for the preservation of organic matter. Moreover, the fault activity and magma eruption caused by the Dongwu Movement can bring a large amount of nutrient elements (such as Fe, MG, P), which stimulated the growth of various organisms in the ocean, thus forming extremely high paleo-productivity. Therefore, the development and distribution of high-quality source rocks in the Gufeng Member of the northern Sichuan Basin were jointly controlled by the high paleo-productivity and strong reduction conditions in the deep-water sedimentary environment of the intra-platform rifts under the extensional tectonic background.
6. Petroleum geological significance

The source rock of the Gufeng Member in the northern Sichuan Basin has high organic abundance, better organic matter types, and stronger hydrocarbon generation potential, with hydrocarbon generation intensity mainly ranging from 5 to $25 \times 10^8$ m$^3$/km$^2$ (Fig. 4). Hereinto, the hydrocarbon generation intensity in Guangyuan-Yilong-Dazhu and Lichuan-Fengjie-Wushan belts can be more than $20 \times 10^8$ m$^3$/km$^2$, which reaches the standard for forming large and medium-sized gas fields. The high-quality source rock in the Gufeng Member is widely distributed and has larger hydrocarbon generation potential, which is of great significance to both Permian-Triassic marine conventional oil and gas exploration and unconventional shale gas exploration in this area.

The high-quality carbonaceous and siliceous mudstone source rock in the Gufeng Member and the limestone of the Maokou Formation are simultaneous heterogeneous deep-water sedimentary products. It can laterally connect with beach reservoirs in different periods of the Maokou Formation to form fine source-reservoir configuration with "side generation and lateral storage" (Fig. 4). The generated oil and gas can migrate to beach reservoirs in different periods of the Maokou Formation in short distance to accumulate, or migrate to karst reservoirs along the regional unconformity surface at the top of the Maokou Formation in long distance to form reservoirs. Therefore, the limestone sedimentary facies change zones of the Gufeng Member and the Maokou Formation in different periods are favorable for natural gas exploration in the Maokou Formation. In addition, the oil and gas generated by the source rock in the Gufeng Member can also vertically migrate through faults to high-quality reservoirs of reef beach facies from the Changxing Formation of Upper Permian to the Feixianguan Formation of Lower Triassic to form reservoirs. At present, the large and medium-sized gas fields of reef-beach facies discovered in this area are mostly located in or close to the hydrocarbon generation center of source rock in the Gufeng Member (Fig. 4).

The high-TOC mudstone in the Gufeng Member is not only an important gas source rock for conventional gas reservoirs, but also a favorable stratum for shale gas exploration. The carbonaceous and siliceous mudstone in the Gufeng Member has average TOC $>2.0\%$ in most wells and profiles, reaching the evaluation standard of Class I shale gas reservoir. At present, the maturity is relatively high, and the pyrolysis gas of organic matter is sufficient and the amount of generated hydrocarbons is large. The content of brittle minerals such as quartz is high in mineral components, and they are mainly biogenic and have strong fracturability. Various types of reservoir spaces such as biological visceral
pores, organic matter pores, intergranular pores, intragranular pores and microfractures are developed. The above conditions are conducive to the enrichment and development of shale gas. The high-TOC carbonaceous and siliceous mudstone with thickness >20m in the Gufeng Member of the study area covers an area of about 2.5×10^4 km^2, with huge shale gas exploration potential, thus it is an important replacement strata for shale gas exploration in the Sichuan Basin.

7. Conclusions
It is confirmed that high-quality source rock was widely developed in the Gufeng Member at the deposit end of the Middle Permian Maokou Formation in the northern part of the basin, with thickness mainly between 5-40 m, high and large variation scope of TOC. The organic matter is mainly type II, and there are various types of hydrocarbon-generating organisms. Currently, it is chiefly in over mature stage inside the basin, and in mature-high mature stage in the periphery of the basin. The deep-water sedimentary environment, high paleo-productivity and strong reducibility in the intra-platform rifts provided favorable preservation conditions and jointly controlled the development and distribution of high-quality source rock in the Gufeng Member of northern Sichuan Basin under the background of extensional structure. The high-quality source rock in the Gufeng Member has great hydrocarbon generation potential, which is of great significance to the exploration of marine conventional natural gas and shale gas in the study area.

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