ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

Characteristics of Gray Source Rock Gas Reservoirs in The First Member of Maokou Formation in Southeastern Sichuan

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Abstract

The gray source rock gas reservoir in the first member of the Middle Permian Maokou Formation in southeastern Sichuan has unique geological characteristics and is an important unconventional natural gas reservoir. Through the observation of rock slices and scanning electron microscopy and the analysis and processing of existing sample data, the reservoir characteristics of the first member of Maokou Formation are clarified, and the reservoir evaluation system and evaluation of the first member of Maokou Formation are established based on its characteristics. The results show that the first member of Maokou Formation mainly develops a set of tight limestone source rock reservoirs with low porosity and low permeability, which are mainly composed of limestone and bioclastic micrite. The reservoir space is dominated by micro-fractures and inorganic pores, with a small amount of organic pores. The pore morphology of the reservoir is complex and changeable. It is filled with clay minerals, calcite and talc. Micropores, mesopores and macropores are developed, and the pore size is mainly distributed in 1.5 nm to 60.4 nm. There is a certain positive correlation between total organic carbon (TOC) and porosity. At the same time, the geographical distribution trend of TOC content in limestone source rocks is consistent with the distribution trend of porosity, which shows a gradual increase from northwest to southeast.

Keywords

Southeast Sichuan basin; First member of Maokou formation; Grey source rock gas; Reservoir characteristics.

1. INTRODUCTION

The southeastern Sichuan region is located in the southwest end of the broom-like structure development area east of the Huayingshan fault in the southeastern Sichuan Basin, spanning the low-steep fold belt in southern Sichuan and the high-steep fold belt in eastern Sichuan[1-3]. It is located in the slope belt of the eastern margin of the Caledonian paleo-uplift in Longnvsi, central Sichuan, and became an important component of the Luzhou paleo-uplift during the Indosinian period. Due to the continuous compression of the Jiangnan-Xuefeng orogenic belt to the northwest, the main form of the NE-trending structure was formed in the Yanshan period, and then it was reformed by the north-south compression-torsion strike-slip fault and finalized in the Himalayan period. At present, the Da 'an exploration area is generally characterized by a NE-trending, wide syncline, and narrow and steep anticlines. The fold tectonic deformation zone[4-8].

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

The Maokou Formation in the study area belongs to the middle Permian strata. The main lithology is light gray and gray-white massive pure limestone, which is 40-450 meters thick. According to lithology and fossils, it can be divided into four sections from bottom to top. This group is in integrated contact with the underlying Qixia Formation and in parallel with the overlying Longtan Formation[9]. Maokou Formation is of great significance for oil and gas exploration.

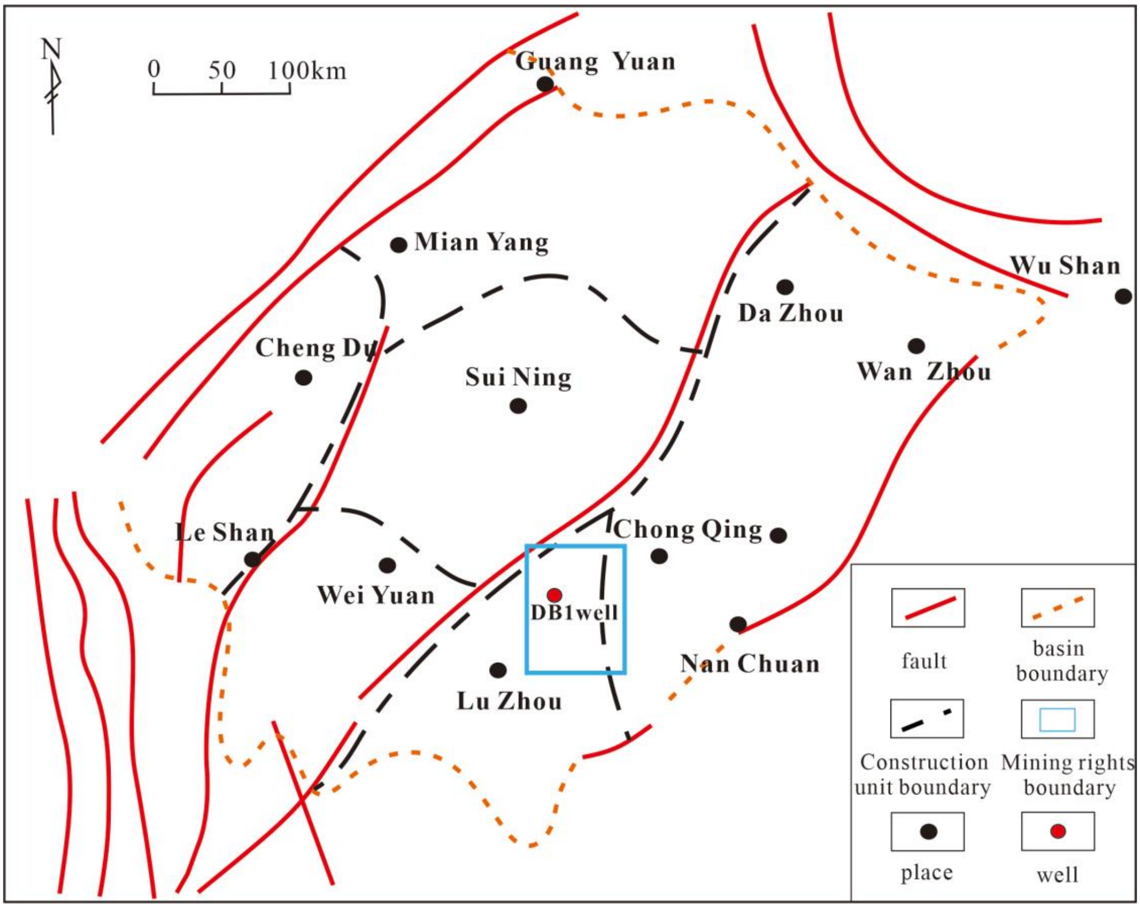

Figure 1. Structural division and study area location of Sichuan Basin

2. ANALYSIS OF RESERVOIR PETROLOGICAL CHARACTERISTICS

2.1. Macroscopical character

At the beginning of the formation of the Maokou Formation in the Sichuan Basin, the invasion of the ocean reached its peak, while the southeast of Sichuan was generally deep in water and relatively low in hydrodynamic force[10]. At this stage, the main sedimentary type is outer gentle slope facies, which is represented by eyeball limestone. The so-called ' eyeball ' is actually a light-colored tumor-like structure, and the gray-black limestone that encapsulates these ' eyeballs ' is called ' eyelid '. This difference between the eyelids and the eyeballs reveals the rapid changes in water dynamics and oxygen content at that time (Figs.2a, b).

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

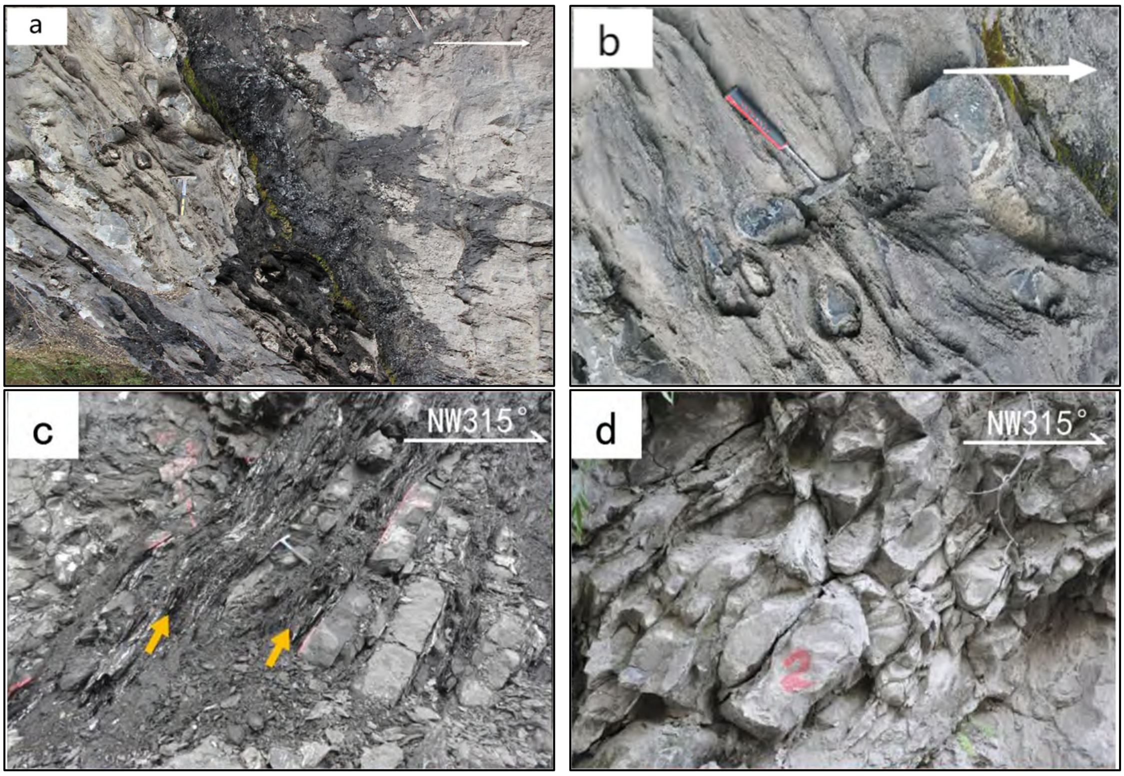

Figure 2. Field outcrop of the first member of Maokou Formation in southeastern Sichuan

According to its composition and particle structure, eyeball limestone can be classified as bioclastic micrite limestone (Fig.2d). The color is mainly gray, with a medium to thick layered structure. There is a gradual contact between the eyeball and the eyelid. The size and frequency of the eyeball have certain regularity. It is mainly developed in the lower part of the first member of Maokou Formation and the upper part of the first member of Maokou Formation. It is a carbonate sediment formed during the rapid deposition period.

The eyelid limestone is gray-black on the core, wrapped with gray eyeball limestone to form output. According to its composition and particle structure, it can be classified as marl limestone (Fig.2c). The color is dark gray to grayish black, and the fresh surface is grayish black, thin to medium layered structure, with obvious horizontal bedding, similar to the shale of the Longmaxi Formation. Mirror-like scratches can be observed in the eyelid limestone on the cross section. It is mainly developed in the lower part of the first member of Maokou Formation and the middle and lower part of the first member of Maokou Formation. The directional arrangement of its biological debris indicates that the water environment at that time was relatively deep and the water flow power was relatively weak[11]. In terms of physical properties, the eyelid limestone usually shows higher gamma ray absorption value and lower resistivity.

2.2. Microscopic characteristics and mineral composition

The eyeball limestone is composed of eyelid and eyeball, in which the eyelid lithology is dominated by marl limestone, and the eyeball lithology is dominated by bioclastic micrite limestone. Under the polarizing microscope, it can be found that there are significant differences in the content of biological debris in the developed rhythmic layer, which is mainly manifested in different layers, and the content of biological debris in the marl layer is usually higher than that in the adjacent limestone layer.

The composition of marl limestone includes micritic calcite, clay minerals and a large number of bioclastics. The content of bioclastics is between 15 % and 30 %, while the argillaceous content is between 25 % and 40 %. Compared with limestone, the fossils of brachiopods and

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

foraminifera in marl are well-preserved, but other types of biodetritus are not well-preserved. Paired ostracod shells are rarely found, and debris particles are generally small and difficult to identify species. Mudstone layers are often greatly affected by compaction, and the arrangement of clastic particles often shows a certain direction. Quartz, siliceous veins and cracks are occasionally seen (Fig.3b, c, d, g, i).

The particles of bioclastic micritic limestone are mainly composed of bioclasts, with a content of 15 % ~ 30 %. Most of the biological debris in the limestone is well preserved and shows no signs of compaction. The crystals of this type of rock have different degrees of self-shape, and most of the crystals are shaped. There are dissolution cracks and pores in the local area, and these structures are filled with mud. Through further analysis of core thin sections, it is found that bioclastic micrite limestone generally does not have obvious bedding. Its bioclastics mainly include algae, brachiopods, ostracods and sea lilies, and the abrasion phenomenon is relatively less. In addition, the content of algae in bioclastic micrite is more abundant than that in marl, while the content of crustaceans is relatively less (Fig.3a, e, f, h).

In the mineral composition of the rock, calcite and dolomite are the two main components, followed by quartz, clay minerals and pyrite, and the content decreases in turn. Among them, calcite and dolomite account for a relatively high proportion, with an average of 85.77 %, quartz accounts for an average of 6.04 %, and clay minerals are mostly talc, with an average proportion of 4.405 %. Specifically, the content of carbonate minerals in bioclastic micritic limestone is 70.1 % ~ 98.2 %, while the content of quartz is 0.03 % ~ 20.5 %, and the content of clay minerals is 0.05 % ~ 10.21 %. In marl limestone, the content of carbonate minerals is 65.32 % ~ 90.11 %, the content of quartz is 0.03 % ~ 9.75 %, and the content of clay minerals is 5.54 % ~ 30.63 %.

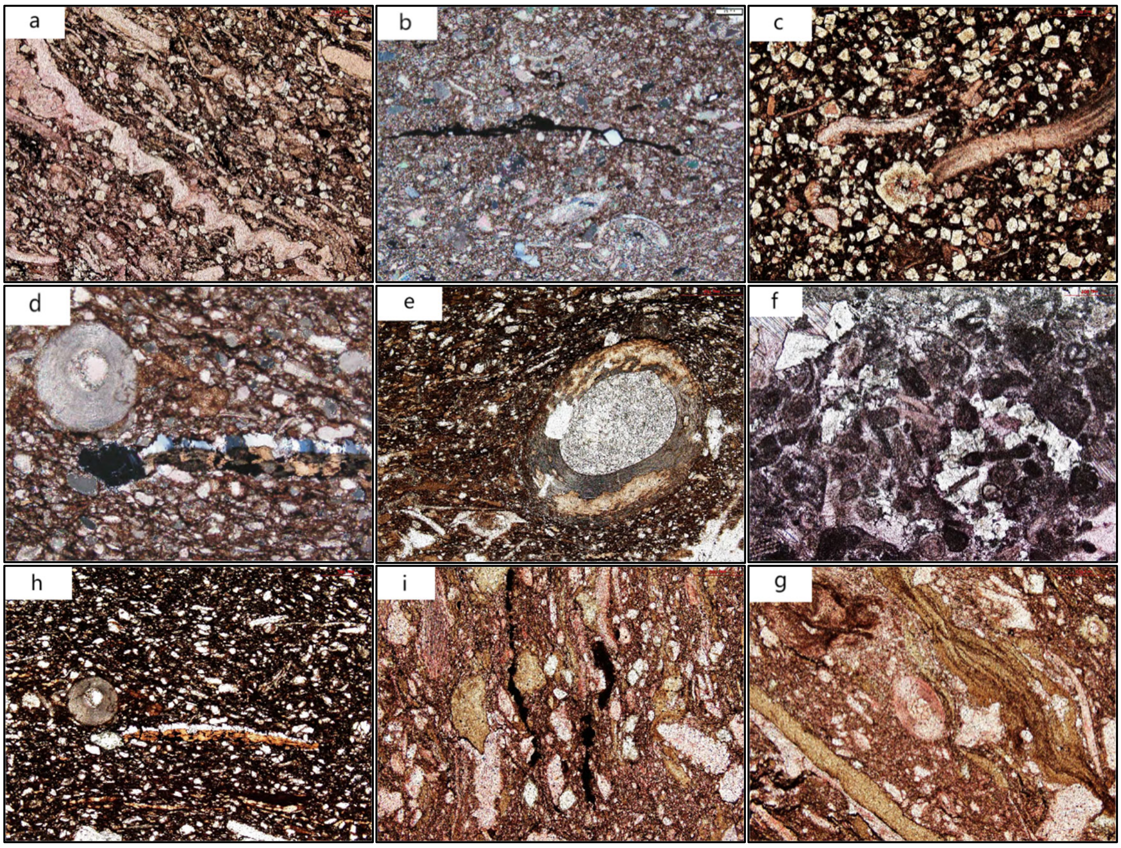

Figure 3. Microscopic characteristics of thin sections of the first member of Maokou Formation in southeastern Sichuan area

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

Vertically, in the lower part of the Maokou Formation, the content of clay minerals is 0.7 % ~ 1.1 %, the content of carbonate minerals is 77.5 % ~ 86.5 %, and the content of quartz is 3.3 % ~ 8.7 %. In the middle of the first member of Maokou Formation, the content of clay minerals is very low, the content of carbonate minerals is 65 % ~ 96.6 %, the content of quartz is 1.1 % ~ 11.8 %, and only a small amount of clay minerals are found at the top and bottom of the section. The clay mineral content is 0.1 % ~ 0.4 %, the carbonate mineral content is 82.5 % ~ 87.3 %, and the quartz content is 5 % ~ 5.5 % in the upper part of the first member of Maokou Formation. On the whole, the content of clay minerals and quartz shows a trend of increasing first and then decreasing from the bottom to the top, and the content of clay minerals in this section is relatively high (Figure 4).

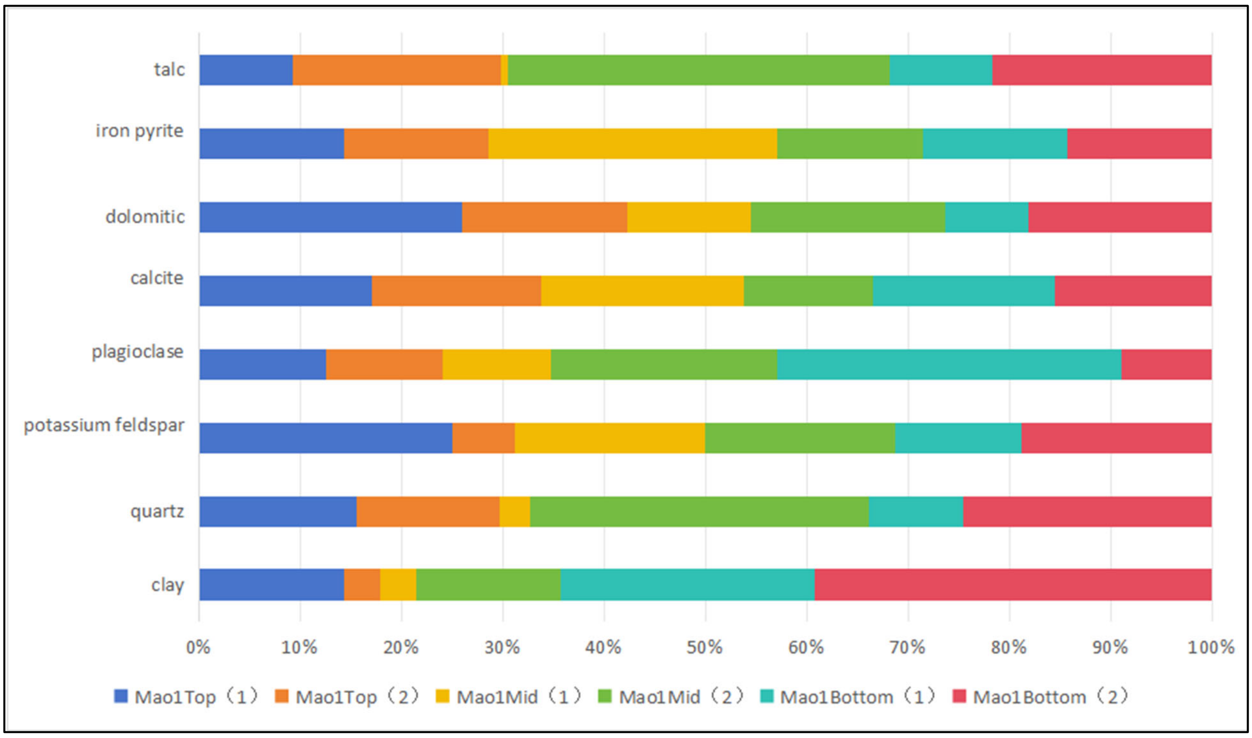

Figure 4. The whole rock mineral composition accumulation bar chart of the first member of Maokou Formation in southeastern Sichuan

3. RESERVOIR SPACE TYPE

By scanning and analyzing the samples of marl reservoir in the first member of Maokou Formation, the reservoir space can be classified into three different types : organic pore, inorganic pore and micro-fracture. Among them, the proportion of organic pores is relatively low, and a complex pore system is constructed by many microcracks and inorganic pores at the nanometer to micron level[12]. This system is connected to each other through talc gaps or intergranular gaps, and has a good fluid penetration ability, forming a 'hole-slit-network 'structure.

3.1. Organic matter pore

(1) Talc-encapsulated organic pores

A large amount of organic matter and talc can be observed in the intergranular pores of carbonate rocks, and talc often surrounds the organic pores in a fibrous shape. The pores of this type of organic matter range from 10 nm to 23 nm in diameter and develop a sponge-like structure (Fig.5a, b).

(2) Independent organic pores

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

It is mainly distributed in the voids between calcite crystals. Some maintain a good rounded shape, and others are affected by diagenesis, showing the characteristics of tension and bending. Most of them are closely related to the edges of calcite crystals, and occasionally coexist with talc. The pores of organic matter are rich, and some pores are connected to each other, with different sizes, from 1nm to 500nm (Fig.5c, d).

(3) Intercrystalline organic pores

Under the electron microscope, it can be observed that framboidal pyrite and pyrite aggregates are associated with calcite and talc. There is a small amount of organic matter in the crystal gap of pyrite. The pores of this kind of organic matter are generally small, usually in the range of 40 nm in diameter. These characteristics indicate the reducing sedimentary environment in which the pores are developed (Fig.5e, f).

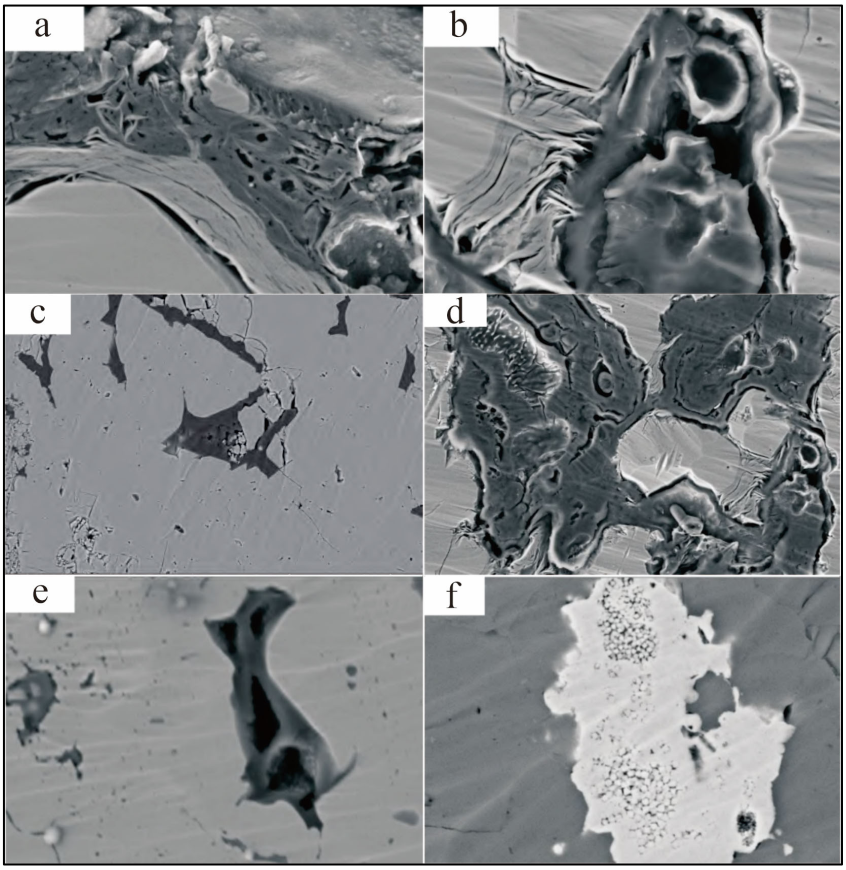

Figure 5. Scanning electron microscope picture of organic pore

3.2. Inorganic pore

The inorganic pores developed in the rocks of the first member of the Maokou Formation mainly include intergranular pores, intercrystalline pores, intercrystalline pores and dissolution pores.

(1) Intergranular pores

The voids between the particles of the sediment and between the particles and the substrate are called intergranular pores. Such pores are formed by compaction after the deposition process, and are generally developed between different components such as lime mud, siliceous, internal debris, and biological debris. The pore size varies from 500 to 2000 μ m, and the edges are mostly irregular bays. Most of the pores are not filled and are mostly isolated, so their connectivity is relatively poor (Fig.6a, b).

(2) Intercrystalline pores

Lime-mudstone generally has high density. Under the electron microscope, it can be found that there are many intergranular pores in calcite or dolomite, and some of them are intergranular pores between pyrite crystals. The holes are mostly in a regular polygonal shape, with a diameter range of 5nm to 6μm. A small number of pores are connected to each other, but the overall connectivity is poor (Fig.6c, d).

(3) Dissolution pores

A small amount of pores formed on the surface of dolomite crystals can be observed under an electron microscope. The width is between 100 and 200 μ m, and the distribution is uneven, showing a variety of forms, including round, oval, polygonal, etc. The pores have good connectivity with each other and can be used as effective reservoir space. This kind of pores may be caused by different dissolution strength, mainly developed in the upper part of the first member of Maokou Formation and the lower part of the first member of Maokou Formation. At the same time, authigenic quartz filler can be observed in the dissolution pores (Fig.6e, f).

(4) Grain edge hole

A certain radian can be observed in the pores composed of calcite, quartz, dolomite, clay minerals and organic matter, which can be seen in the whole section of Maokou Formation. The pore diameter is between 10 and 1000 nm. Most of the gaps are about 50 nm wide and have good connectivity (Fig.6g).

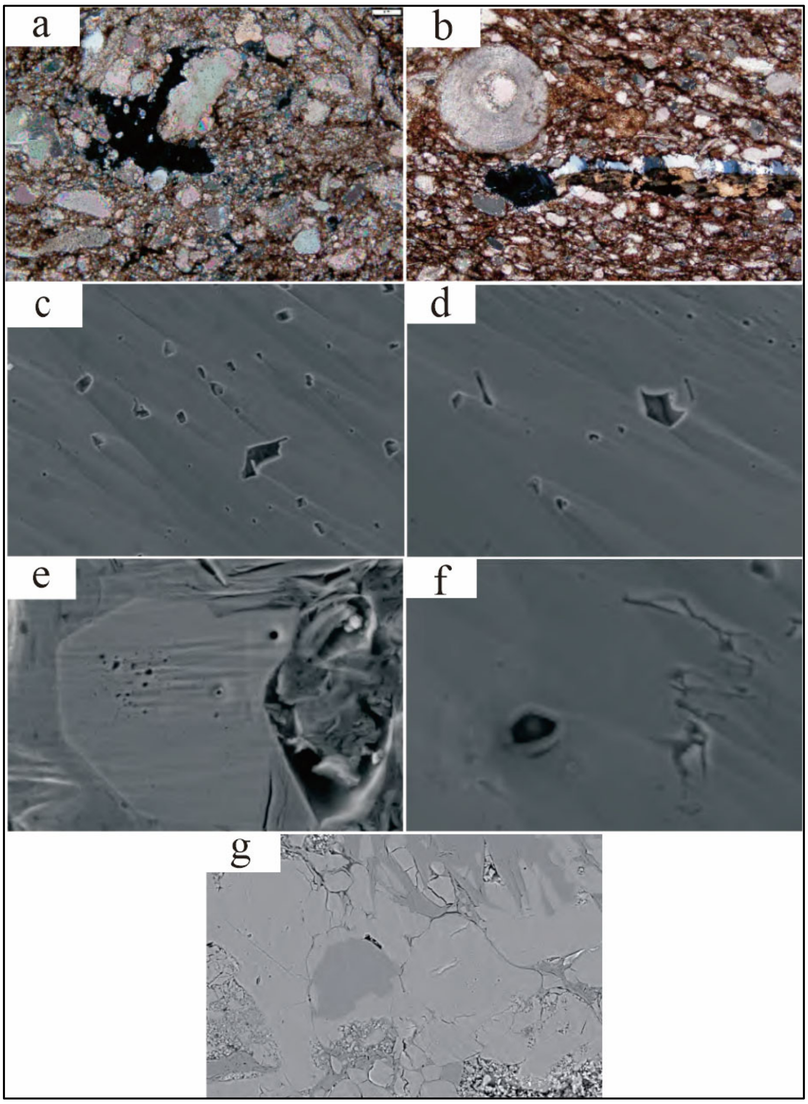

Figure 6. Inorganic pore scanning electron microscope and mineral thin section diagram

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

3.3. Tiny crack

The rock samples of the first member of Maokou Formation have high content of fragile minerals, which makes it easy to produce cracks under the action of tectonic force. The cracks are mainly low angle, and there are also a small number of high angle cracks. Under the microscope, the rock slices show relatively straight crack characteristics, and the filling phenomenon of oil and gas and mud is obvious[13]. At the same time, dissolution cracks are also developed in the study area, with various forms, including dendritic and reticular structures. The length and width of the cracks are 1000 to 5000 nm and more than 200 nm, respectively. These dissolution fractures have good connectivity and can be used as effective oil and gas migration channels. They are also one of the important reservoir space types of the Maokou Formation in the study area. In rock samples, the main types of cracks observed include talc cracks, grain edge cracks and stress cracks.

(1) Talcum slit

Under the electron microscope, it can be found that the mineral particles of argillaceous limestone are filled with a large amount of clay minerals, mainly talc. Talc and clay minerals are cemented in a bottom-like manner[14]. The talc shows a loose structure under the microscope, showing obvious schistosity characteristics, and there are a large number of small cracks. These micro-fractures constitute the main storage space of the reservoir. The fracture distribution of talc is limited, and there are many fractured double layers on the crystal layer. Talc cracks can also be observed around the organic matter, and the morphology of such cracks is affected by the edge of the organic matter, showing diversity, such as bending and flat (Fig.7a, b).

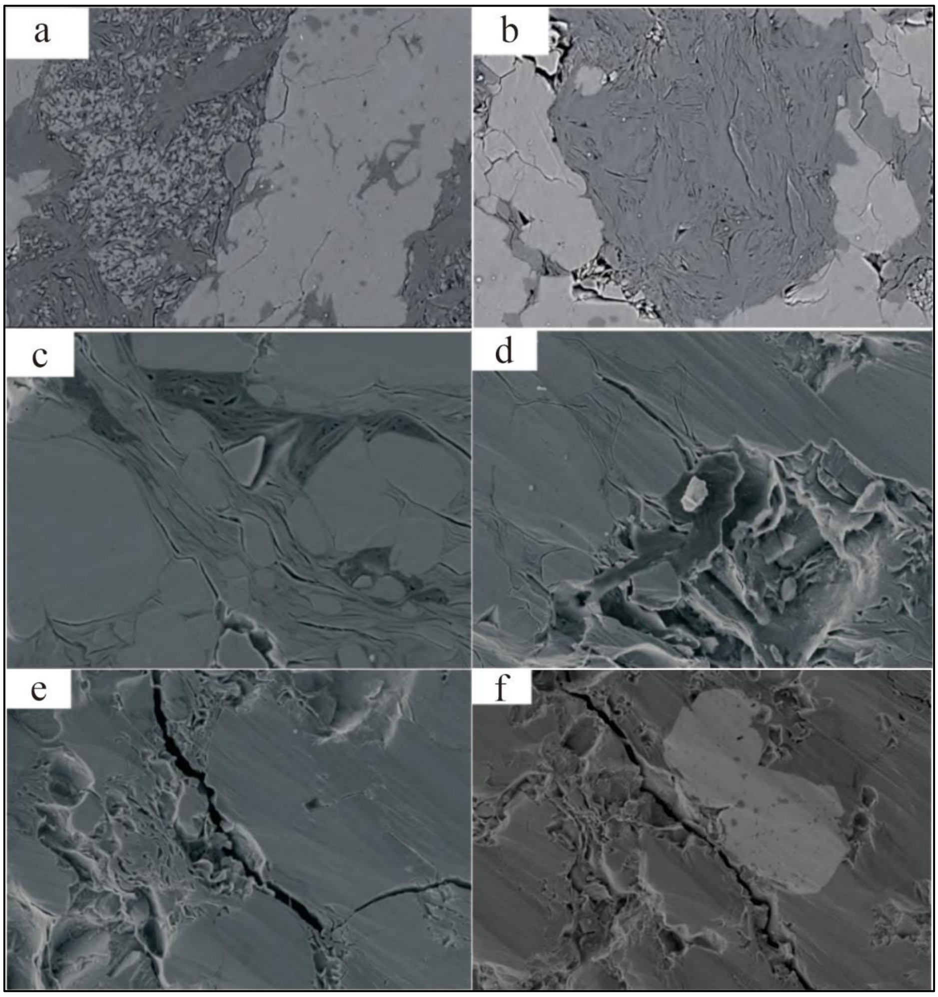

Figure 7. Scanning electron micrograph of microfractures

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

(2) Grain edge seam

Contact with talc or organic matter can be observed at the edge of the carbonate mineral, and the width of such cracks is between 60 nm and 4 μm. Due to the shape and contour of mineral particles and the influence of organic matter, such cracks can show a variety of forms such as bending and straight. Fractures have good connectivity and form complex dendritic or network structures. At the same time, dissolution fractures around different minerals are also interconnected, making such fractures a key channel for reservoir fluid migration and diffusion (Fig.7c, d).

(3) Stress seam

The cracks formed by the influence of stress are common in the macro scale of the Maokou Formation in the study area. Under the observation of polarizing microscope and scanning electron microscope, most of these cracks have no filling material, and only a few are filled with silica. The width of these cracks is from a few microns to hundreds of microns, and most of them show a longer form, and mainly grow along the talc cracks and mineral edges. For the process of oil and gas migration, such fractures play a key role in guiding the flow (Fig.7e, f).

4. PHYSICAL CHARACTERISTICS

In the study area, the porosity of the first member of the Maokou Formation is distributed between 0.32 % and 5.72 %, with an average of 1.9 %, while the number of samples with porosity exceeding 2 % accounts for 22.1 % (Fig.8a). The permeability is in the range of $0.001 \times 10^{-3}\mu m^2 \sim 1.542 \times 10^{-3}\mu m^2$, with an average of $0.59 \times 10^{-3}\mu m^2$ (Fig.8b). The number of samples with permeability in the range of $0.011 \times 10^{-3}\mu m^2 \sim 0.110 \times 10^{-3}\mu m^2$ reaches 30.5 %. In the longitudinal direction, the upper part of the Maokou Formation and the lower part of the Maokou Formation are roughly the same in terms of porosity, but the footwall is slightly better. Specifically, the total porosity of the upper part of the first member of the Maokou Formation (hanging wall) ranges from 0.07 % to 4.95 %, the average porosity is 1.92 %, the effective porosity is 0.01 % ~ 4.95 %, and the average effective porosity is 1.88 %. The total porosity of the lower plate is 0.54 % ~ 4.66 %, the average porosity is 2.05 %, the effective porosity is 0.47 % ~ 4.42 %, and the average effective porosity is 2.04 %, which is better than the upper plate.In addition, the total porosity of the lower part of the first member of the Maokou Formation (the footwall of the fault) is 0.12 % ~ 5.77 %, the average porosity is 2.55 %, the effective porosity is 0.12 % ~ 5.66 %, and the average effective porosity is 2.51 %. The overall performance is better than the upper part of the first member of the Maokou Formation. In the first member of Maokou Formation, 27 % of the samples have a permeability of more than $0.1 \times 10^{-3}\mu m^2$.The permeability values of these samples are between $(0.0017 \sim 10.0261) \times 10^{-3}\mu m^2$, and the average permeability is $0.4767 \times 10^{-3}\mu m^2$.

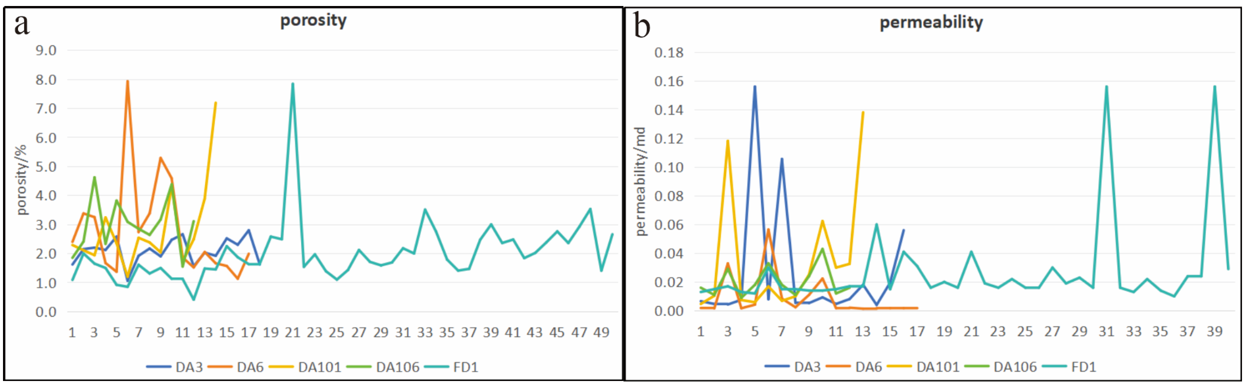

Figure 8. Porosity-permeability line chart of samples from several wells in the first member of Maokou Formation in southeastern Sichuan Basin

In lithology analysis, the rock type of the first member of Maokou Formation is eyeball limestone, which can be divided into two different rock types : eyelid limestone and eyeball limestone[15]. The eyelid limestone is mainly composed of marl limestone, while the eyeball limestone is mainly composed of micritic limestone containing bioclastic. The porosity of eyelid limestone is generally higher than that of eyeball limestone, the specific value is 1.5 % ~ 3 %, the average porosity is 2.48 %, and the porosity of some samples is more than 7 %. The porosity of eyeball limestone is low, mainly distributed in 1.0 % ~ 1.5 %, with an average porosity of 1.2 % and a minimum porosity of 0.5 % (Fig.9a). The reservoir lithology of the first member of Maokou Formation is mainly eyelid limestone, that is, gray-black argillaceous limestone, and its porosity shows an increasing trend from northwest to southeast. There is also a positive correlation between porosity and TOC value (total organic carbon content) of limestone marl reservoirs, both of which show a gradual increase from northwest to southeast.

Permeability is one of the key indicators to measure material properties. According to the experimental data, the index changes in the range of (0.0017 ~ 10.0261) × $10^{-3}μm^2$, with an average of 0.4767 × $10^{-3}μm^2$. This conclusion is consistent with the research data. The permeability of limestone in the eyelid part is significantly higher than that in the eyeball part. The permeability range of limestone in the eyeball is (0.021 ~ 0.418) × $10^{-3}μm^2$, with an average of 0.062 × $10^{-3}μm^2$. In contrast, the permeability of the eyelid limestone is higher, and its value is between (0.0019 ~ 10.216) × $10^{-3}μm^2$, with an average of 0.69 × $10^{-3}μm^2$ (Fig.9b).

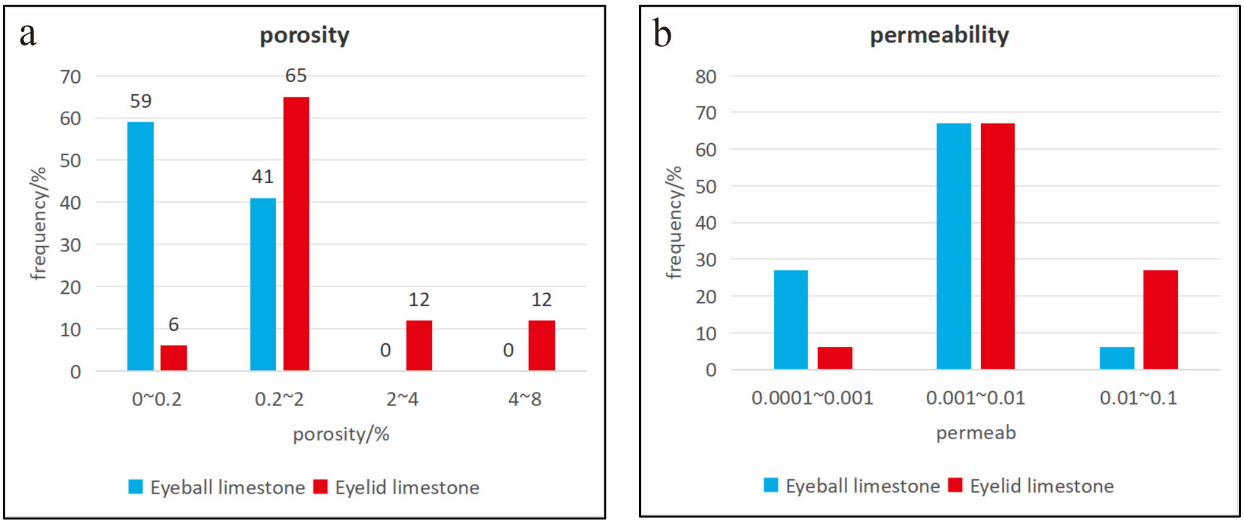

Figure 9. The frequency histogram of porosity and permeability distribution of core rock samples in the first member of Maokou Formation in southeastern Sichuan

5. ORGANIC GEOCHEMICAL CHARACTERISTICS

The TOC (total organic carbon) analysis of the core samples showed that the value ranged from 0.31 % to 5.2 %, and the average level was 1.56 %. For rock debris samples, the TOC content is distributed between 0.3 % and 2.8 %, with an average of 1.22 %. Vertically, the abundance of organic matter in the upper part of the first member of Maokou Formation is the most abundant. At the same time, the average TOC of the upper part of the first member of Maokou Formation is 1.31 %, while the average TOC of the lower part is slightly higher, which is 1.58 %. In contrast, the TOC in the middle of the first member of Maokou Formation is only 0.71 %, while the average TOC in the lower part of the first member of Maokou Formation is 0.95 % (Fig.10). In different sedimentary structures of the first member of Maokou Formation, the organic matter content of marl limestone shows significant differences. The measured TOC content of the eyeball limestone is 0.31 % ~ 0.69 %, while the eyelid limestone is higher, and its TOC content can reach 1.57 % ~ 5.20 %. Therefore, the upper part of the Maokou Formation

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

has better source rock characteristics than other sub-members, and the organic matter abundance of the eyelid limestone is significantly higher than that of the eyeball limestone.

Further combined with the analysis of the pyrolysis parameters of the limestone source rock of the first member of the Maokou Formation, it can be found that the kerogen type is mainly type III, and the R_o value is 1.91 % ~ 2.38 %, indicating that the whole has entered the mature dry gas generation stage. The T_{max} value shows a large fluctuation, ranging from 372 °C to 546 °C, with an average value of 439 °C. The distribution range of hydrocarbon generation potential $S_1 + S_2$ is 0.21 ~ 2.24 mg / g, with an average of 0.69 mg / g, and the range of hydrogen index IH is 8.40 ~ 137.39 mg / g, with an average of 42.74 mg / g.

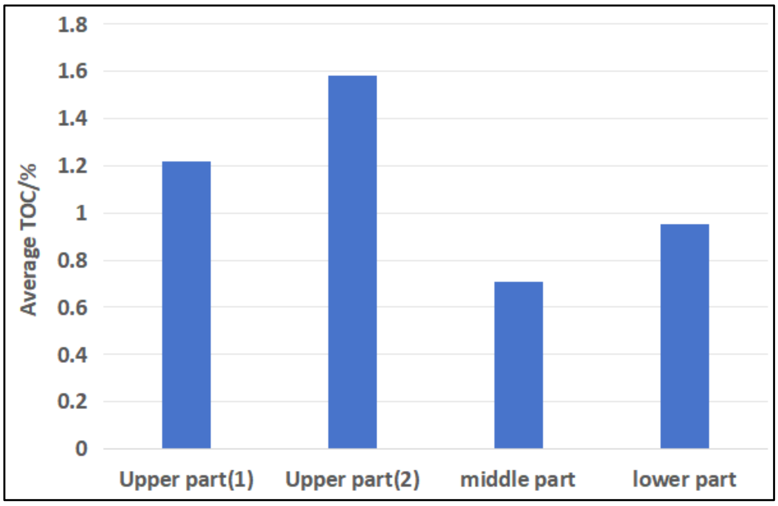

Figure 10. TOC content diagram of each sub-member of Maokou Formation in southeastern Sichuan

6. CONCLUSION

(1) A set of tight gray source rock reservoirs with low porosity and low permeability are mainly developed in the first member of Maokou Formation in southeastern Sichuan. The lithology is mainly lime marl and bioclastic micrite limestone.

(2) The limestone source rock reservoir of the first member of Maokou Formation is a fracture-pore reservoir. The reservoir space types are mainly micro-fractures, inorganic pores and organic pores. Among them, the proportion of grain boundary pores and dissolution pores in inorganic pores is higher, while organic pores are not dominant in the reservoir, and organic matter is rare. Inorganic pores dominate in the matrix pores. Microfractures are also important reservoir spaces for limestone source rocks, including grain boundary fractures, talc fractures and stress fractures. Among them, talc fractures and grain boundary fractures account for a higher proportion in fractures, showing a strong reservoir potential.

(3) The pore morphology of the reservoir in the first member of Maokou Formation is complex and changeable, and it is filled with clay minerals, calcite and talc. Micropores, mesopores and macropores are developed, and the pore size is mainly distributed in 1.5 ~ 60.4nm, showing a large range of changes. The mesopores with a pore size of 2 ~ 50 nm constitute the main pore volume. Macropores larger than 50 nm contribute less pore volume. The micropores less than 2 nm only occupy a small part of the pore volume.

(4) There is a positive correlation between total organic carbon (TOC) and porosity. TOC content and quartz and talc play an important role in the formation of reservoir micropore structure. At the same time, the geographical distribution trend of the TOC content of the

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

limestone source rock is consistent with the distribution trend of the porosity, which shows a gradual increase from the northwest to the southeast.

ACKNOWLEDGEMENTS

On the completion of this thesis, I sincerely thank all those who have given me support and help. Special thanks to my mentor, he with its profound academic foundation and rigorous academic attitude, carefully guided me, so that I benefit a lot in the research process. At the same time, I also want to thank my classmates for their academic exchanges and discussions, providing me with a lot of valuable inspiration. In addition, I am deeply grateful to my family, whose silent support and selfless dedication have created a good learning environment for me. Finally, I would like to extend my most sincere thanks to all the teachers and friends who have given me care and encouragement in the writing of the thesis. It is your company that enables me to successfully complete this study.

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ISSN: 2472-3703 DOI: 10.6911/WSRJ.202502_11(2).0008

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