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# Characteristics and Controlling Factors of Tight Marl Reservoirs with an Eyelid-Shaped Structure of the First Member of the Deep Maokou Formation in Eastern Sichuan

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**Abstract:** Tight marl is a special type of unconventional oil and gas resource, and the study on its reservoir characteristics and controlling factors is of immense scientific significance. In this paper, 113 core samples of marl from Gouxi Area, Eastern Sichuan were selected. Based on organic carbon, pyrolysis, X-ray diffraction of whole rock, and X-ray diffraction of clay analysis, the reservoir evaluation of eyelid-shaped limestone in the first member of Maokou Formation was carried out. The results show that there are obvious differences between eyelid-shaped limestone reservoirs and eyeball-shaped limestone reservoirs in the target stratum. Eyelid-shaped limestone is mainly distributed in the lower members a and c of the first member of Maokou Formation. It could be the main reservoir of low porosity and permeability tight marl, as its developed apertures, micro-fractures, and pore throat structure are obviously better than that of the eyeball-shaped limestone. As eyelid-shaped limestone features obvious self-generation and self-storage characteristics, the deep-water and low-energy sedimentary environment provides it with a large amount of highly brittle minerals and clay minerals as well as a favorable reservoir-forming background for diagenetic evolution and organic matter adsorption of clay minerals in the later period. The transformation of sepiolite into talc through diagenesis provides a large number of shrinkage joints for the reservoir, which are an effective space for tight gas accumulation.

**Keywords:** argillaceous limestone; controlling factors; Eastern Sichuan; eyelid-shaped structure; tight reservoir

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## 1. Introduction

In recent years, China has made some remarkable achievements in unconventional oil and gas exploration and production, and oil and gas output is experiencing a golden period of rapid development. A large number of explorations have confirmed that unconventional oil and gas are the main source of future energy industry growth [1,2]. Judging from the current unconventional oil and gas exploration breakthroughs, the proven reserves of shale gas have been found in the Longmaxi Formation in the southeast of Sichuan Basin; a major breakthrough in shale oil exploration has been made in the Lucaogou Formation, Jimusar Sag of Junggar Basin; and tight gas sandstone reservoirs will be the primary source for the increase in oil reserves and production in the Ordos Basin [3–5]. Tight marl reservoirs in deep marine facies are a special type of unconventional oil and gas resource. However, compared with the above typical unconventional oil and gas resources, the research on tight marl reservoirs in the natural gas field is still at an initial stage in terms of exploration theories and evaluation methods [6,7]. Thus, there is an urgent need to use existing unconventional oil and gas testing methods, carry out basic research on the occurrence conditions and controlling factors of tight marl reservoirs and expand new fields and types of unconventional oil and gas exploration.

Gray and dark gray marls are widely distributed in Maokou Formation in the east of Sichuan Basin, which features eyelid- and eyeball-shaped limestone structures [8]. To explore the unconventional new fields of marl in the first member of Maokou Formation in Eastern Sichuan, CNPC and Sinopec recently carried out old well reexamination and risk exploration for this formation. According to the existing drilling data, there are active oil and gas deposits in the first member of Maokou Formation, and they possess good gas-bearing properties. There are 19 test wells in the first member of Maokou Formation, and 15 of the wells have natural gas production to varying degrees. Among them, the acid-fracturing transformation of Tongtan Well 1 in the first member of Maokou Formation has ensured the production of 310,000 $m^3$ of industrial gas per day with a 12 mm nozzle, which further suggests that the first member of Maokou Formation has good natural gas exploration prospects [9,10]. However, due to the low overall exploration level of the first member of Maokou Formation, current explorations are not on a large scale, and there are insufficient studies on tight marl reservoir space and controlling factors. Based on this weak link, in this paper, we systematically analyzed the source and reservoir characteristics and controlling factors of eyelid- and eyeball-shaped marl by using marl samples from the first member of Maokou Formation in Gouxi Area, Eastern Sichuan, thus providing a basis for further natural gas exploration in the first member of Maokou Formation, Eastern Sichuan.

## 2. Overview of the Study Area and Sample Collection

### *2.1. Geological Background*

Located in the south-central part of the Asian continent, Sichuan Basin is one of the four great basins in China. On the plane, it can be divided into five tectonic units—low and gentle tectonic zone in Northern Sichuan, low and steep tectonic zone in Western Sichuan, low and steep tectonic zone in Southern Sichuan, flat and gentle tectonic zone in Central Sichuan, and high and steep tectonic zone in Eastern Sichuan (Figure 1). Before the Permian sedimentation, the basin was affected by the stretching and tension of the Paleo-Tethys Ocean—it was a passive continental margin basin and experienced large-scale exposure and denudation [11,12]. Till the Permian sedimentation, the crust sank completely. Except for the Dabashan Archicontinent in the north, Longmenshan Archicontinent in the northwest, Kangdian Archicontinent in the west, and Jiangnan Archicontinent in the east that emerged out of the water surface in island chains or islets, the upper Yangtze Archicontinent was completely submerged, and extensive transgression made the Middle Permian cover the strata of Carboniferous and other ages [13]. In this study, the target stratum is in the sedimentation period of the first member of Maokou Formation. The ancient landform was relatively low, the water was relatively deep from Guangyuan in Northwestern Sichuan and Guang'an in Northeastern Sichuan to the east of Chongqing, and it was mainly deposited in the deep and gentle slopes. From the regional sedimentation setting, the sedimentation period of the first member of Maokou Formation was favorable for the development and distribution of marine source rocks.

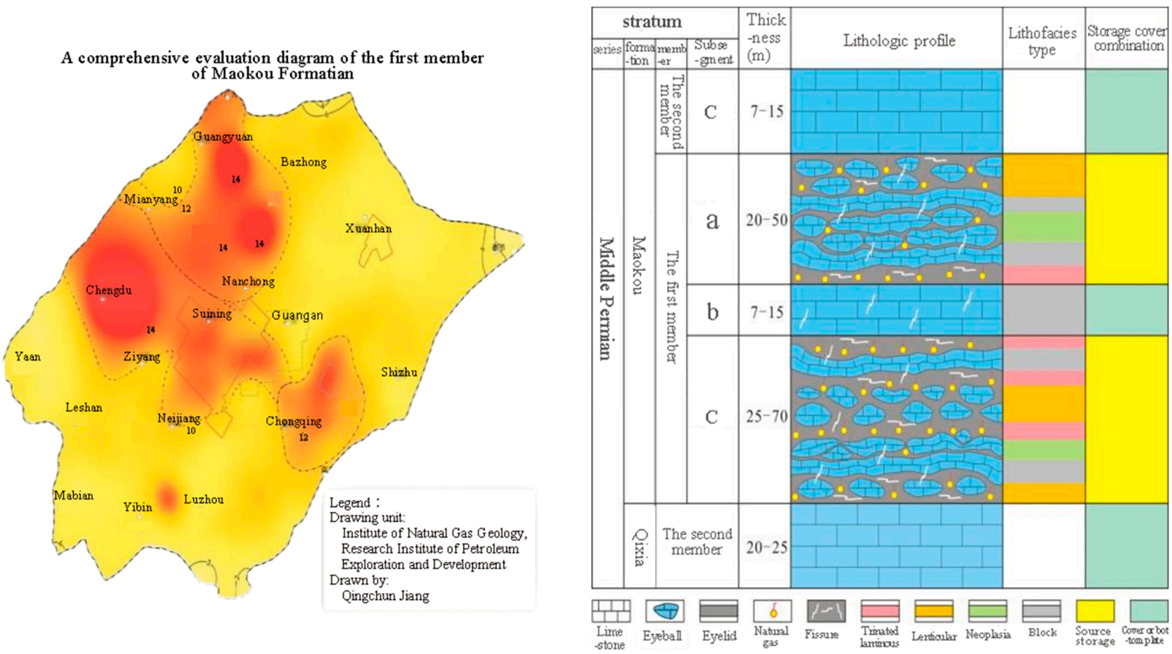



**Figure 1.** Overview of work area and reservoir cap combination.

### 2.2. Sample Collection

The strata thickness of the first member of Maokou Formation in Sichuan Basin gradually increased from southwest to northeast, and the overall thickness is between 50 m and 130 m. Vertically, the first member of Maokou Formation has obvious eyelid- and eyeball-shaped structures, wherein the "eyelid" wraps around the "eyeball" in the shape of veins and curves, the "eyelid" is darker than the "eyeball" and the internal debris content is higher than the "eyeball", and it is in directional alignment. By combining lithological characteristics and logging curves, the first member of Maokou Formation can be vertically divided into Section c, b, and a from bottom to top. The tendency of strata thickness of the lower member c is consistent with the first member of Maokou Formation, and the thickness is between 25 m and 75 m. The difference in thickness of the lower member b is relatively small and ranges between 7 m and 20 m, and there are two thickness centers in Northern Sichuan and Southeastern Sichuan, respectively. The strata thickness of the lower member a of the first member of Maokou Formation varies greatly, ranging between 20 m and 50 m. The resistance has stable characteristics of "2 lows and 1 high" in these areas. The thickness and curve characteristics of the first member of Maokou Formation in Northeastern Sichuan and Northwestern Sichuan are similar, suggesting that their sedimentary environments are close. There is a topographic rupture in the transition area from Central Sichuan to Eastern Sichuan, and storm filling takes place in the lower part, forming eyeball- and eyelid-shaped limestone [14].

As a brand-new unconventional oil and gas field of carbonate rocks in Sichuan Basin, there has been limited exploration of tight marl reservoirs in the first member of Maokou Formation. To explore the scale and gas-bearing property of unconventional argillaceous limestone reservoirs in the first member of Maokou Formation, the Xintan Well 1 was deployed in Gouxi Block, Eastern Sichuan. The Xintan Well 1 was drilled to a depth of 4470 m in the first member of Maokou Formation. After drilling was completed, samples were collected 5 times in this section, with a total core length of 80.4 m. In this study, a total of 113 geochemical and reservoir analysis samples were collected from the limestone system of the first member of Maokou Formation, and the characteristics and controlling factors of reservoir performance of the eyelid-shaped limestone and eyeball-shaped limestone in the first member of Maokou Formation were focally analyzed and compared.

## 3. Experimental Analysis

To accurately obtain the key parameters of core geochemistry and reservoir evaluation in the first member of Maokou Formation, 113 samples were collected in this experimental scheme, and organic carbon, pyrolysis, X-ray diffraction of whole rock, X-ray diffraction of clay, and other analysis, were conducted. Based on this, representative limestone samples with different organic carbon content were selected for porosity, high pressure mercury injection, and other experiments, to further confirm the micro-control effect of source rock development in tight limestone reservoirs.

*SY/T 5163-2018 X-ray Diffraction Analysis Method for Clay Mineral and Common Non-clay Minerals in Sedimentary Rock* was adopted for X-ray of whole rock analysis and diffraction analysis, X-ray diffrtometer was used to test 113 limestone samples of different organic carbons to determine the mineral composition and content of the samples. *SY/T 5346-2005 Rock capillary pressure measurement* was adopted for high-pressure mercury injection. After the samples were processed with the AutoPoreIV9505 pore analyzer, liquid mercury was injected, and the pores were detected under high pressure. The measured ambient temperature was 21.3–21.5 °C and the relative humidity was 40–44%. The maximum mercury injection pressure was 200 MPa, and the corresponding minimum pore throat was 3.68 nm. *SY/T 5162-2014 Analytical method of rock sample by scanning electron microscope* was adopted for scanning electron microscope (SEM), and the main equipment used was SEM and X-ray energy spectrometer. After the samples were washed with oil, dried in a dust-free condition, and vacuum coated, the rock structure, pore type, and interstitial material were observed, clear images were taken, and accurate mineral identification was conducted [15–17].

## 4. Results and Discussion

### *4.1. Basic Characteristics of Tight Marl Reservoir*

#### 4.1.1. Lithological Characteristics

Based on the characteristics of cores, slices, and logging curves, according to the changing characteristics of lithology, the strata in the study area can be further subdivided into the second member of Maokou C Formation, the first member of Maokou A Formation, the first member of Maokou B Formation and the first member of Maokou C Formation from old to new. Affected by the strong uplift of the Dongwu movement, the upper strata of the Maokou Formation are generally denudated in the basin, the first member of Maokou Formation is the sea invasion system of sequence one, the whole is deep gentle slope deposition, the total thickness of 50~130 m, the conventional logging shows obvious “two low resistance clamp and one high resistance” three section characteristics, it is evident that nodular limestone mainly developed in the first member of Maokou Formation, and cyclothems of eyelid- and eyeball-shaped limestone and marl developed vertically (Figure 2).

Eyeball-shaped limestone refers to nodular or spherical tight limestone. The dark-gray micrite is tight and has poor plasticity and well-developed fractures. These expanded and eroded to form caves and then completely filled by calcite in the later period. The logging curve is characterized by “2 highs and 3 lows” (high density and high resistance; low interval transit time, low neutron, and low gamma) [14,18,19]. Eyelid-shaped limestone refers to the layered marl wrapped around the eyeball, which is mostly gray-black argillaceous bioclastic limestone. Micro-fractures developed locally in the core, and are filled with mud and calcite. The logging curve is characterized by “3 highs and 2 lows” (high interval transit time, high neutron, and high gamma; low density and low resistance) [20]. From the vertical lithologic distribution, the eyelid content of the lower member c of the first member of Maokou Formation is higher than the lower member a of the first member of Maokou Formation, and the eyeball is the main part of the lower member b of the first member of Maokou Formation. The fractures mainly developed in the middle and upper parts of the lower member b of the first member of Maokou Formation and the lower member a of the first member of Maokou Formation, and the fractures are filled with calcite.

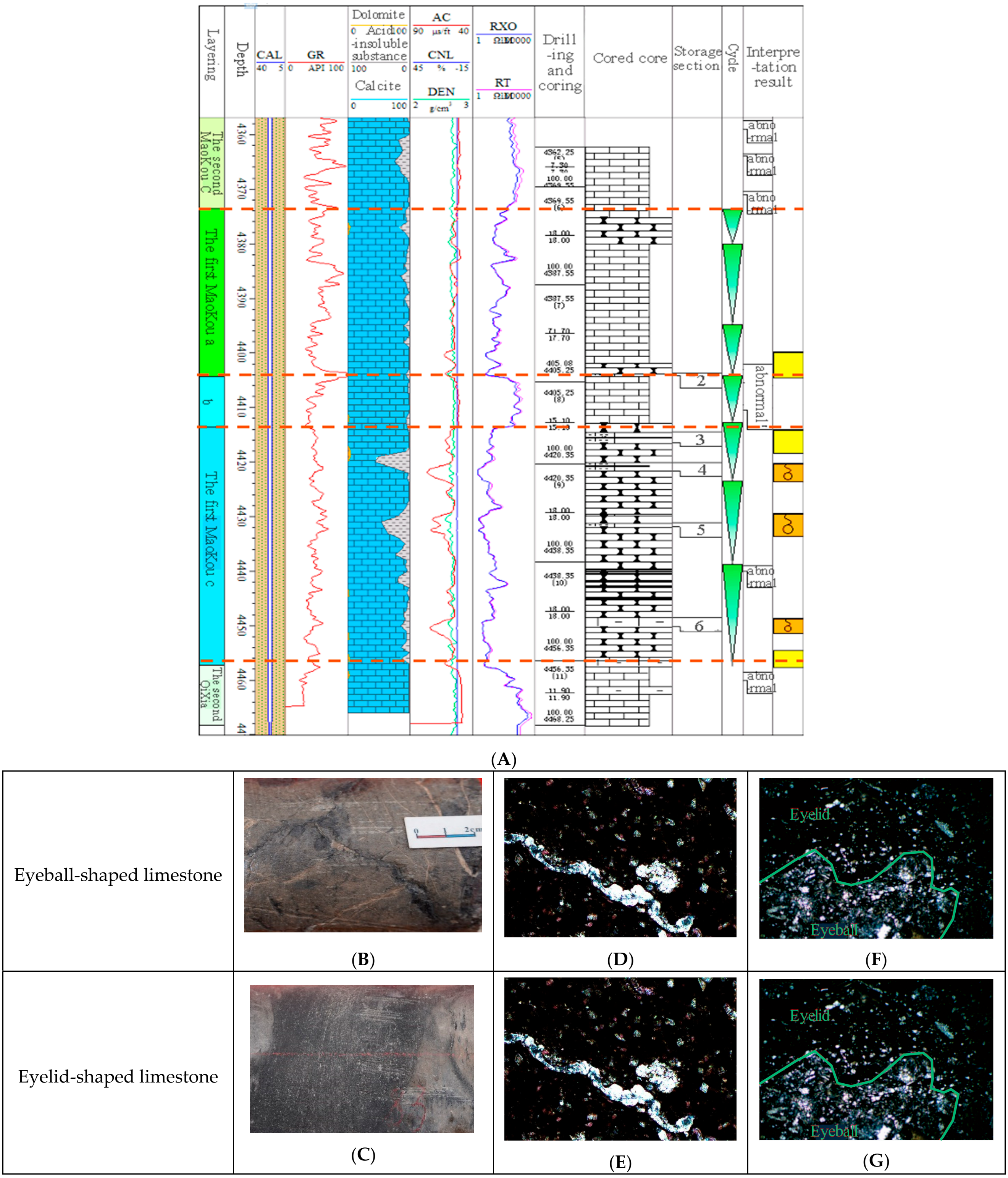



**Figure 2.** Comprehensive lithological histogram of the first member of Maokou Formation of the Xintan Well 1. (**A**) Comprehensive lithological histogram of the Xintan Well 1. (**B**) The lower member b of the first member of Maokou Formation 4407.65 m. (**C**) The lower member c of the first member of Maokou Formation 4454.65 m. (**D**) The lower member c of the first member of Maokou Formation Formation 4420.52 m. (**E**) The lower member c of the first member of Maokou Formation 4420.52 m. (**F**) The lower member c of the first member of Maokou Formation 4451.30 m. (**G**) The lower member c of the first member of Maokou Formation 4451.30 m.

#### 4.1.2. Physical Characteristics

Physical property is the most direct index that reflects the capacity of limestone reservoirs. From the porosity analysis of the first member of Maokou Formation, the limestone of the first member of Maokou Formation is relatively tight and has a distribution of between 0.9% and 4.4%, wherein, 90% of the samples are lower than 2.5% and all samples with porosity of over 3.0% are distributed in the eyelid-shaped limestone. Comparing the average porosity of eyeball-shaped limestone and eyelid-shaped limestone, the average porosity of eyelid-shaped limestone is 2.84%, which is obviously higher than the 1.68% average porosity of eyeball-shaped limestone. Eyelid-shaped limestone is concentrated in the lower member c of the first member of Maokou Formation. This further indicates that the deep layer in the study area continues to develop high-porosity zones with respect to the tight background.

#### 4.1.3. Mineral Characteristics

The mineral compositions of the first member of Maokou Formation are mainly calcite, followed by quartz and clay minerals with a small amount of dolomite, and the differences between eyeball- and eyelid-shaped limestone are obvious (Table 1). Eyeball-shaped limestone is mainly bioclastic micrite containing 82–99% calcite, 0–9.5% talc, 0–9% clay minerals, 0–9% quartz, and 0–5% dolomite. Eyelid-shaped limestone is mainly argillaceous bioclastic limestone containing 9–78.9% calcite and 8–63% clay minerals, which included 0–63% talc, 0–38.4% clay minerals, 2–29% quartz, and 1–26% dolomite.

In conclusion, the talc, clay minerals, quartz and dolomite content of eyelid-shaped limestone were low. Therefore, it has high brittleness, mainly develops inorganic pores, organic pores and microcracks, pore seepage correlation is better, and the microscopic pore structure is obviously better than eyeball limestone, which is beneficial to oil and gas storage. These control factors of eyelid marl provide the basis for the next exploration of natural gas in eastern Sichuan.

**Table 1.** Average statistical table of main mineral compositions of tight marl in the first member of Maokou Formation in Xintan Well 1.

| Mineral Composition % | The Lower Member a of the First Member of Maokou Formation | | The Lower Member b of the First Member of Maokou Formation | | The Lower Member c of the First Member of Maokou Formation | |
|---|---|---|---|---|---|---|
| | Eyelid-Shaped Limestone | Eyeball-Shaped Limestone | Eyelid-Shaped Limestone | Eyeball-Shaped Limestone | Eyelid-Shaped Limestone | Eyeball-Shaped Limestone |
| Quartz | 9.66 | 4.35 | 8.18 | 2.81 | 10.55 | 3.44 |
| Calcite | 71.20 | 83.34 | 79.38 | 88.64 | 66.25 | 79.23 |
| Dolomite | 5.51 | 3.46 | 1.95 | 1.00 | 4.84 | 5.82 |
| Clay minerals | 14.02 | 9.01 | 10.34 | 8.04 | 13.36 | 10.88 |
| Talc | 27.43 | 37.37 | 37.60 | 30.29 | 28.00 | 22.71 |
| Aliettite | 61.78 | 51.43 | 63.67 | 65.14 | 57.92 | 66.43 |
| Illite | 11.27 | 12.00 | 7.33 | 6.40 | 14.54 | 19.10 |

### *4.2. Tight Marl Reservoir Space and Pore Throat Characteristics*

#### 4.2.1. Characteristics of Reservoir Space

The secondary corrosion pores of the eyeball did not develop, and only a few stylolites and tensile fractures developed. Most of the stylolites are filled with asphalt, while most of the tensile fractures are completely filled with calcite; half-filled tensile fractures are seen occasionally, and residual asphalt is found in calcite intercrystalline pores. The eyelid-shaped limestone mainly developed inorganic and organic pores, wherein, inorganic pores included calcite or dolomite intercrystalline corrosion pores, intercrystalline pores, and talc shrinkage holes (fractures). Organic pores are nano-sized, and the pore diameter is mainly tens to hundreds of nm, which is controlled by the abundance of organic matter. Furthermore, there are also micro-fractures that mainly developed in the interior, at the edge of brittle mineral particles, and between macrophyllites (Figure 3).

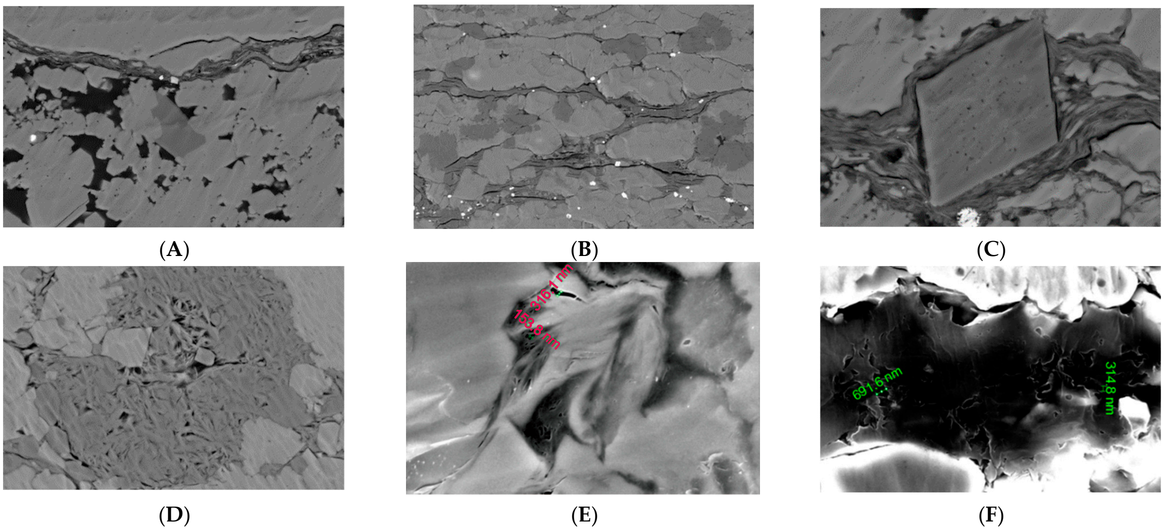



**Figure 3.** Types of pore development in the reservoir in the first member of Maokou Formation. (**A**) Residual asphalt of calcite intercrystalline pores in the Heping Well 1. (**B**) Calcite intercrystalline pores and micro-fractures in the Heshen Well 3. (**C**) Dolomite development corrosion holes in the Heping Well 1. (**D**) Talc shrinkage holes (fractures) in the Hebao Well 1. (**E**) Organic nanopores in the Heshen Well 3. (**F**) Irregular organic pores in the Heping Well 1.

4.2.2. Characteristics of Mercury Injection Pore Throat

Based on the high-pressure mercury injection data, it is evident that with the increase in depth, the skewness of the pore throat of the first member of Maokou Formation in the capillary pressure curve changed from fine skewness to coarse skewness, the mercury injection curve is gentle, and the average value of maximum mercury injection saturation is above 80%; these reservoir characteristics indicate good sorting of pore throat size [21]. The displacement pressure of eyelid-shaped limestone is low, and the oil and gas entered and accumulated easily. Compared with eyeball-shaped limestone, the average porosity of eyelid-shaped limestone is 2.84%, and the maximum pore throat radius and average pore throat radius are higher (Table 2). Eyelid-shaped limestone has a stronger reservoir capacity and better pore throat connectivity. Overall, the pore throat characteristics of the eyelid-shaped limestone of the tight marl in the first member of Maokou Formation are obviously better than that of the eyeball-shaped limestone. Organic pores are an important reservoir space and mainly feature micron pores and nano pores, with low-porosity and permeability-based accumulation. The micropores are more developed near 4430 m (the lower member c of the first member of Maokou Formation), and there is a relatively high pore zone with respect to the tight background (Figure 4).

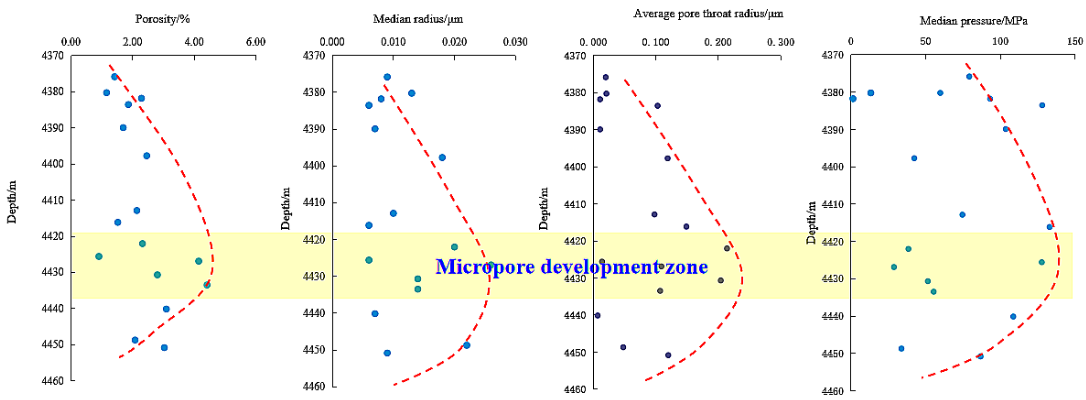



**Figure 4.** Comparison of microscopic pore development zones.

**Table 2.** Analysis table of eyelid and eyeball-shaped limestone pore throat structures in the first member of Maokou Formation of Xintan Well 1.

| Depth | Porosity (%) | Pore Throat Radius (μm) | | | Pore Throat Distribution | | Sorting Coefficient | Mean Radius (μm) | Structure Coefficient | Relative Sorting Coefficient | Characteristic Structural Parameters | Homogeneity Coefficient | Mercury Saturation | | Maximum Exit Efficiency of Instrument (%) | Displacement Pressure (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Maximum | Average | Median | Peak Position (μm) | Peak Value (%) | | | | | | | Maximum | Final Residue | | |
| | *φ* | *Ra* | *Rp* | $R_{50}$ | *Rv* | *Rm* | *Sp* | *Dm* | *Φ* | *D* | *1/Dφ* | *α* | *Smax* | *Sr* | *We* | *Pcd* |
| 4412.85 | 2.137 | 1.092 | 0.098 | 0.01 | 0.01 | 19.92 | 1.79 | 0.016 | 2.552 | 112.07 | 0.003 | 0.09 | 84.021 | 47.731 | 43.192 | 0.673 |
| 4416.12 | 1.518 | 1.092 | 0.149 | 0.006 | 0.006 | 14.453 | 2.113 | 0.023 | 4.203 | 92.359 | 0.003 | 0.136 | 70.219 | 46.946 | 33.144 | 0.673 |
| 4422.01 | 2.319 | 1.555 | 0.214 | 0.02 | 0.016 | 23.7 | 2.457 | 0.059 | 13.24 | 41.387 | 0.002 | 0.137 | 86.818 | 60.864 | 29.954 | 0.473 |
| 4426.86 | 4.144 | 1.09 | 0.109 | 0.026 | 0.025 | 19.978 | 2.022 | 0.037 | 6.168 | 54.828 | 0.003 | 0.1 | 91.862 | 63.319 | 31.072 | 0.674 |
| 4430.65 | 2.803 | 1.57 | 0.204 | 0.014 | 0.01 | 20.66 | 2.382 | 0.045 | 14.583 | 52.669 | 0.001 | 0.13 | 88.448 | 63.042 | 28.724 | 0.468 |
| 4433.46 | 4.414 | 1.087 | 0.107 | 0.014 | 0.01 | 14.361 | 2.098 | 0.027 | 6.368 | 78.201 | 0.002 | 0.099 | 85.566 | 41.574 | 51.412 | 0.676 |
| 4440.12 | 3.094 | 0.018 | 0.007 | 0.007 | 0.006 | 24.748 | 0.762 | 0.008 | 0.021 | 92.039 | 0.507 | 0.419 | 80.821 | 57.772 | 28.518 | 41.345 |
| 4448.7 | 2.079 | 0.268 | 0.048 | 0.022 | 0.025 | 14.401 | 1.983 | 0.037 | 0.609 | 52.944 | 0.031 | 0.181 | 80.811 | 52.109 | 35.517 | 2.743 |
| 4450.81 | 3.028 | 1.089 | 0.12 | 0.009 | 0.006 | 20.861 | 2.08 | 0.025 | 5.422 | 82.785 | 0.002 | 0.11 | 90.518 | 44.752 | 50.561 | 0.675 |
| 4397.7 | 2.457 | 1.083 | 0.119 | 0.018 | 0.016 | 19.492 | 2.243 | 0.048 | 4.354 | 46.324 | 0.005 | 0.11 | 92.26 | 59.896 | 35.079 | 0.678 |
| 4425.56 | 0.905 | 0.053 | 0.014 | 0.006 | 0.006 | 13.053 | 1.226 | 0.012 | 0.022 | 98.975 | 0.464 | 0.26 | 69.024 | 19.646 | 71.538 | 13.776 |

*4.3. Analysis of Controlling Factors of Tight Marl Reservoir*

4.3.1. Lithologic Combination of Self-Generation and Self-Storage Controlled the Vertical Enrichment of Oil and Gas

The tight marl reservoir features self-generation and self-storage, and the lower member b of the first member of Maokou Formation is relatively tight. Natural gas mainly occurred in the lower members a and c of the first member of Maokou Formation (with a high content of eyelid-shaped limestone), featuring obvious vertical stratum control. The high organic matter abundance of pelitic bioclastic limestone or argillaceous bioclastic limestone of the eyelid-shaped limestone is the material basis for source-reservoir integration and in-situ enrichment, which provides source rock and reservoir space for oil and gas enrichment [22,23]. At the same time, there is an abundance of oil and gas in the low-energy eyelid-shaped limestone zone, and it has a well-developed micro- and nano-pore throat system. The reservoir is relatively tight with a porosity of 4–12% (Table 2) and a permeability of less than 1 mD, featuring low porosity and permeability. The micropore development section shares good correspondence with the organic matter enrichment section, which is similar to the "self-generation and self-storage" accumulation characteristics of shale gas [24] and controlled carbonate reservoir.

4.3.2. Deep-Water and Low-Energy Sedimentary Environment Controlled the Development of Self-Generated and Self-Stored Limestone Reservoirs

From the beginning of the Permian in Sichuan Basin, the land sank, and deposition commenced. Under the transgression background, the Permian Maokou Formation covered the strata of different ages [25]. In this study, the target stratum of the first member of Maokou Formation is an arc-shaped development zone with large thickness in Eastern Sichuan. Affected by the Dongwu Movement at the end of the Middle Permian, it suffered from karstification such as strong denudation and corrosion, corrosion of underflow, and dilution of terrigenous debris (Figure 5) [26,27], which made its ancient landform relatively low and water body relatively deep. It developed into a deep-water and low-energy sedimentary environment of deep and gentle slope carbonate marine facies, which is favorable to the development of tight marl reservoirs.

Sedimentary environment is one of the important factors to control tight marl reservoirs. The first member of Maokou Formation reserved the original appearance of transgression at the Chihsian age, and the whole basin was an epicontinental sea environment with normal salinity and abundant organisms, depositing a set of marine carbonate rocks [28]. The eyelid-shaped limestone in the first member of Maokou Formation was originally deposited in a stagnant deep water environment with high shale content, abundant biodetritus, and highly abundant TOC (Figure 5). However, the shale content of eyeball-shaped limestone is relatively low, which indicates that the hydrodynamic conditions were strong when the original sediments were formed and the supply of shale was rather limited. Different hydrodynamic sedimentary environments had an important impact on the reservoir. Comparatively speaking, the deep-water environment of eyelid-shaped limestone abounding in biodetritus is more favorable to improving the quality of tight marl reservoirs.

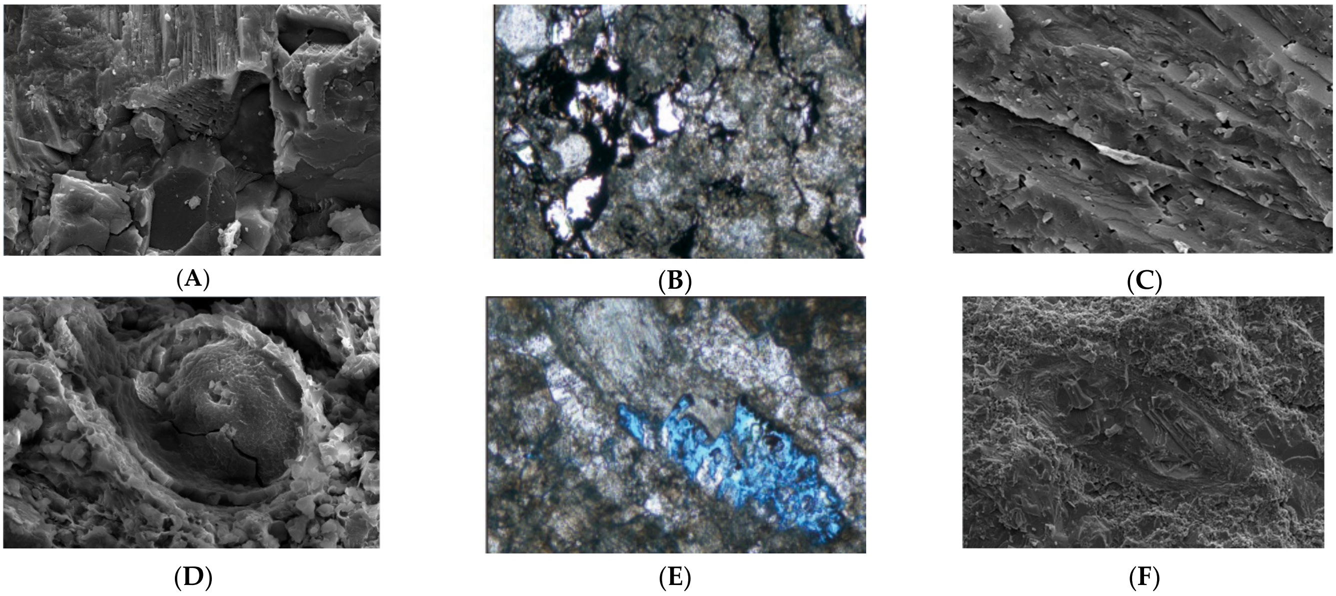



**Figure 5.** Microscopic slices of corrosion and biodetritus in Eastern Sichuan. (**A**) Intracrystalline corrosion holes of calcite in the first member of Maokou Formation. (**B**) Eyelid development intercrystalline corrosion pores and corrosion seams in the first member of Maokou Formation. (**C**) Development of intercrystalline pores in the first member of Maokou Formation. (**D**) Biodetritus and micro-fractures developed in the first member of Maokou Formation. (**E**) Development of intragranular corrosion pores of eyelid biodetritus in Maokou Formation. (**F**) Biodetritus filling in the first member of Maokou Formation.

#### 4.3.3. Improvement of Organic Matter Adsorption by Highly Brittle Minerals and Clay Minerals Controlled the Physical Properties of Reservoirs

The lithology of the first member of Maokou Formation is dominated by bright micritic bioclastic limestone, micritic bioclastic limestone (also known as eyeball-shaped limestone), muddy micritic bioclastic limestone, and argillaceous micritic bioclastic limestone (also known as eyelid-shaped limestone). It is mainly composed of calcite, quartz, clay, and a small amount of dolomite, and the overall sedimentary environment is stable. Different from the tight continental facies reservoirs, the fluid migration of the first member of Maokou Formation was strong at the early diagenetic stage, which led to relatively weak cementation at the later stage. The more developed the intergranular pores, the better the pore connectivity and reservoir space. The clay minerals of the first member of Maokou Formation have an adsorption effect on organic matter [29], while the clay mineral content of the eyelid-shaped limestone is obviously higher than the eyeball-shaped limestone (Figure 6). This is also the key factor for the high organic matter abundance of eyelid-shaped limestone in the lower member c of the first member of Maokou Formation. Shrinkage fractures increased as well, which played a role in improving the reservoir. Besides, the contents of brittle mineral calcite, quartz, and dolomite in the first member of Maokou Formation are relatively high, and micro-fractures formed easily (Figure 7). This is favorable to the optimization of physical properties of reservoirs in this area, at the same time, it is more convenient to calculate the reserves in the study area by using the modern model in the subsequent study [30].

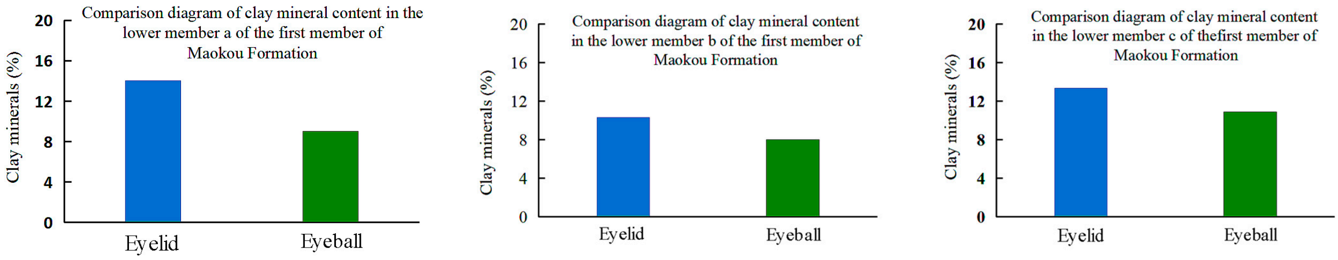
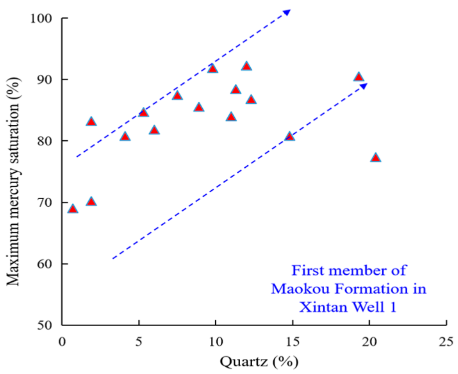



**Figure 6.** Comparison of clay mineral content in the eyelid and eyeball of the first member of Maokou Formation.

(**A**)

(**B**)

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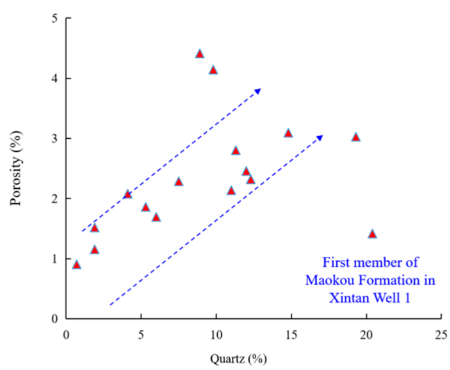


(**D**)

**Figure 7.** Brittle minerals in the first member of Maokou Formation in Eastern Sichuan improved the reservoir. (**A**): In the lower member a of the first member of Maokou Formation (4375.05 m), micrite and fractures developed and were filled with calcite. (**B**): In the lower member a of the first member of Maokou Formation (4383.55 m), fractures were filled with micrite and calcite. (**C**): Quartz and maximum mercury saturation diagram of the First member of Maokou Formation in Xintan Well 1. (**D**): Quartz and porosity diagram of the First member of Maokou Formation in Xintan Well 1.

#### 4.3.4. Diagenesis of Talcization Improved the Effective Reservoir Space of the Target Stratum

The tight marl reservoir in the study area was affected by destructive and constructive diagenesis. It is evident that the eyeball-shaped limestone in the study area was cemented by calcium carbonate at the early diagenesis stage, and was not compacted firmly to a large extent, thus resulting in weak destructive pressure solution. In contrast, the pressure solution of calcium carbonate in the eyelid-shaped limestone is obvious, hence, the eyelid-shaped limestone became loose and porous due to the destructive pressure solution, and the eyeball-shaped limestone was cemented tightly due to the precipitation of calcium carbonate [31–33]. The porosity and permeability of eyelid-shaped limestone are better than that of the eyeball-shaped limestone. The efficient pathway system in the eyelid-shaped limestone increased the effective reservoir space of the corresponding tight marl reservoir, which was favorable for the oil and gas injection in the later period.

The mud in the eyelid-shaped limestone was not terrigenous detrital clay mineral but clay mineral in the constructive diagenesis stage. At the early diagenesis stage, the clay mineral was mainly palygorskite-sepiolite. With the increase of burial depth in the middle and late diagenesis stages, the temperature and pressure increased, the pore fluid in sepiolite discharged, and the intergranular layer chain collapsed and then gradually turned into talc and a small amount of smectite. Talc further replaced sepiolite at the early diagenetic stage, and stucco and organisms at the sedimentary stage [34,35]. Meanwhile, organic matter micropores formed due to hydrocarbon generation at the middle diagenetic stage and talc shrinkage pores (fractures) formed in the process of sepiolite dehydration to talc transformation (Figure 8), became the effective reservoir space.

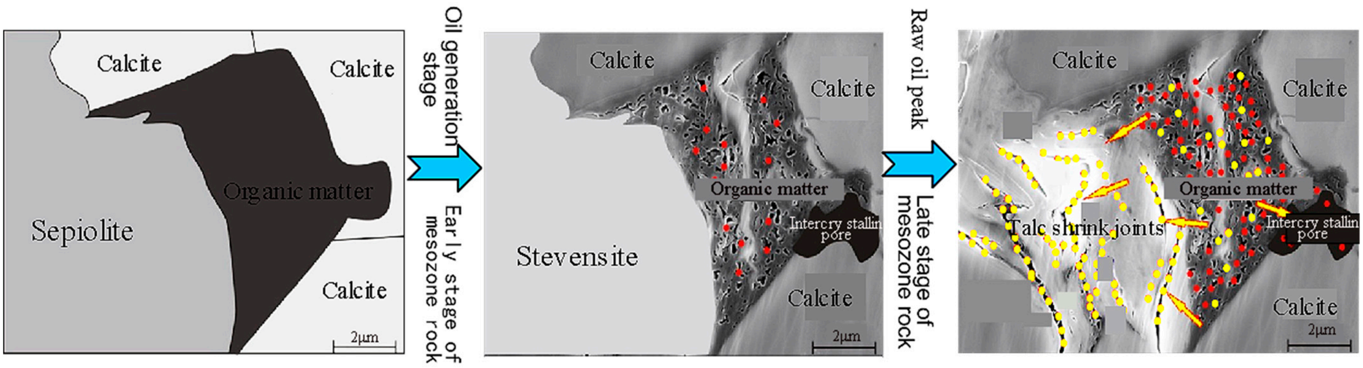


**Figure 8.** Diagram of the formation of organic pores and shrinkage joints in the talc transformation process.

Sepiolite deposited under seawater conditions released a large amount of magnesium ions in the process of constructive diagenesis and talcization and then turned into dolomite in the later period [36]. This was also a necessary condition for the development of pore-type reservoirs with high-quality tight marl in the first member of Maokou Formation. On the one hand, the dolomitization in the buried period transformed tight marl into dolomite, and equimolar metasomatism occurred to calcite in the fluid due to magnesium ions. As dolomite has a smaller molar volume than calcite, the precipitation volume of dolomite is smaller than the dissolution volume of calcite, which led to the increase in rock porosity in the process of metasomatism. On the other hand, a large number of dolomite intercrystalline pores provided a channel for the thermal fluid activity in the later period. When the acid fluid entered the stratum in the later period, [37] it corroded the reservoir, further increasing rock porosity and led to the development of a high-quality reservoir. In this process, the porosity, shrinkage joints, and interlayer fractures of the reservoir increased, and magnesium ions, $SiO_2$, and water molecules were released during diagenesis, forming a large number of organic pores and clay micropores, generating unconventional high-quality reservoirs, and effectively improving the oil and gas accumulation efficiency of tight marl reservoirs containing sepiolite clay minerals.

## 5. Conclusions

(1) The first member of Maokou Formation in Eastern Sichuan Basin is a new and unconventional exploration area of carbonate rocks, in which calcite is the main mineral in the target area, followed by quartz and clay minerals with a small amount of dolomite. It is a deep and gentle slope deposit, which is favorable to the development of marine source rocks. Its whole body is tight with obvious reservoir differences. Eyelid tectonic zone and eyeball tectonic zone are vertically distributed, and they are a tight marl reservoir with low porosity and permeability.

(2) Eyeball-shaped limestone is mainly bioclastic micrite limestone, with a small number of stylolites and tensile fractures developed and concentrated in section b of the first member of Maokou Formation. Eyelid-shaped limestone is mainly argillaceous bioclastic limestone with better correlation between porosity and permeability and rich organic matter; it mainly developed inorganic pores, organic pores, and micro-fractures, and is concentrated in section c of the first member of Maokou Formation.

(3) Eyelid-shaped limestone is characterized by self-generation and self-storage, and its formation is controlled by the sedimentary environment, concentration of brittle minerals, adsorption of clay minerals, and talcization.

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