

Characteristics and Reservoir Evaluation of Dolomite in the Qixia Formation at the Lao Gongqiao Village Profile, Huaying Mountain

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ABSTRACT

This study focuses on the dolomite in the Lao Gongqiao Village profile in the Huaying Mountain. By analyzing field outcrops and thin sections, two types of dolomite occurrences were identified: fine-crystalline dolomite at the bottom of the Qixia Formation and spotted dolomitic limestone in the middle to upper part of the formation. The profile also features saddle-shaped dolomitic cement. The fine-crystalline dolomite has primary porosity mainly in the form of intercrystalline (dissolution) pores, with moderate porosity and low permeability. The spotted dolomitic limestone, with limited dolomitization, has poor reservoir properties. The saddle-shaped dolomite, a later cement, reduces the reservoir space, leading to poorer reservoir performance.

KEYWORDS

Dolomite; Occurrence Types; Reservoir Properties.

1. INTRODUCTION

Natural gas exploration in dolomite reservoirs of the Lower Permian Qixia Formation in the Sichuan Basin has attracted considerable attention in recent years. However, the development characteristics and differences in dolomite reservoirs across various regions remain under study, and the formation mechanisms of these reservoirs need further exploration. To address these issues, this paper makes use of field outcrop data and thin section analyses from the Lao Gongqiao Village profile in Huaying Mountain. We provide a macro-description of dolomite occurrences and identify various dolomite types. Additionally, based on thin section identification and analysis, we describe the lithological types and characteristics of the dolomite, highlighting the micro-macroscopic petrographic features and differences in reservoir space types and reservoir capacity among different dolomite types. This research aims to provide a sedimentary geological basis for future oil and gas exploration in the region.

2. GEOLOGICAL BACKGROUND

The Sichuan Basin lies within the upper Yangtze Plate and is divided into six tectonic belts. The Huaying Mountain area is located within the Sichuan Basin's eastern fold belt. The Sichuan Basin's eastern high-steep fold belt consists of northeast to southward arcuate folds, forming the Huaying Mountain broom-like tectonic system, with significant folding within the region (Zou Yutao et al., 2015). The main fault zone is a compound anticline that extends from Tianchi in Guang'an, Sichuan, in the north to Pijiashan, Hechuan City, in the south. The Lao Gongqiao Village profile is located east of the Huaying Mountain fault and west of the Qiyao Mountain fault, with its eastern side bordering

Neishui, southern connection to Yubei District of Chongqing, and western proximity to the Xiangyu Railway. To the north, it borders Guang'an City, making transportation in the region convenient.

In the Huaying Mountain fold area, secondary folds and faults are well-developed. The oldest exposed strata belong to the Upper Cambrian of the Lower Paleozoic, with missing strata from the Devonian and Lower Carboniferous of the Paleozoic. Well-preserved strata from the Permian and Mesozoic, including Triassic and Jurassic, are present. These strata have undergone crustal uplift and compression, forming large-scale tectonic karst landscapes.

The studied strata belong to the Early Permian Qixia Formation. The upper boundary of the Qixia Formation is in parallel unconformable contact with the overlying Maokou Formation. The base of the Maokou Formation has a set of oolitic limestone, and the lower boundary of the Qixia Formation is in conformity with the Liangshan Formation, which includes black shale and grayish-white claystone. In the basin, the Qixia Formation is mainly composed of limestone, with localized dolomite. The thickness ranges from 100 to 200 meters and is divided into two parts: Qixia Formation I (referred to as Qixia I) and Qixia Formation II (referred to as Qixia II). The early stages of Qixia I deposition formed in an open marine environment, and in the later stages of Qixia I, the sea level relative to the basin dropped. At the top of Qixia I, phenomena such as dissolution channels, caves, and conglomeration related to high-frequency exposure surfaces are commonly observed (Lu et al., 2020). The lithology is characterized by gray-black, medium-thin bedded bioclastic mudstone and bioclastic limestone, with small sections of dolomite at the bottom of the studied profile. The early deposition of Qixia II was influenced by a short marine transgression, followed by a long period of low sea levels (Bai Xiaoliang et al., 2020). At the end of Qixia deposition, regional exposure occurred. The lower part of Qixia II is composed of deep gray and black-gray, medium-thin bedded crystalline and bioclastic limestone, which becomes lighter in color and more bioclastic upward. The middle part consists of gray to dark gray, medium-thin bedded bioclastic limestone. The upper part is characterized by medium-thick bedded “spotted” dolomitic limestone, with uneven dolomitization.

This paper primarily studies the fine-crystalline dolomite at the base of the Qixia Formation and the spotted dolomitic limestone in the middle-upper part. Notably, although Qixia I is a deeper marine environment than Qixia II, the bottom of Qixia I and Liangshan Formation represent contemporaneous, shallow-water overlying deposits, providing the foundation for dolomite development (Gu Zhidong et al., 2014).

3. OVERVIEW OF THE STUDIED PROFILE

The Qixia Formation in the Lao Gongqiao Village profile outcrops over a length of 133.6 meters, with the upper part unconformably contacting thin-bedded nodular limestone, and the lower part in conformable contact with the Liangshan Formation's sandstone. The base of the Qixia Formation consists of a middle layer of shallow gray blocky fine-crystalline dolomite, about 6 meters thick. The lower part of this dolomite is in parallel conformity with the Liangshan Formation, and the upper part is overlain by a set of mudstone and bioclastic limestone. The middle part of the Qixia Formation consists of alternating limestone and mudstone with rhythmic features, occasionally interspersed with siliceous concretionary limestone. Near the top of the Qixia Formation, spotted dolomitic limestone appears, with the upper part consisting of mudstone and bioclastic limestone and the lower part of siliceous concretionary limestone and gray medium-thick bedded mudstone, with saddle-shaped dolomitic cement observed in the siliceous limestone.

4. PETROGRAPHIC CHARACTERISTICS OF DOLOMITE

4.1. Fine-crystalline Dolomite

This type of dolostone appears as light gray blocks with smooth fracture surfaces. The surface is covered with yellow clay, and some of the rock shows developed fissures, which are filled with calcite. When diluted hydrochloric acid is dropped on the surface, it reacts vigorously (Figure 1a). Under the polarizing microscope, the calcite veins exhibit distinct conjugate joints with an angle of approximately 75° . The calcite veins intersect each other in a dendritic pattern or form karst channels (Figure 1c). Some calcite is found between the dolomite grains (Figure 1d). Dolomite crystals are irregular, with the degree of euhedral crystallization varying from bottom to top. The lower and upper parts consist of euhedral to subhedral crystals (Figure 1b), while the middle part contains subhedral to anhedral crystals (Figure 1e). The grain size typically ranges from 50 to 100 μm . Intercrystalline pores are developed, with a heterogeneous distribution of porosity (Figure 1e). The dolomite crystals are often dirty, typically yellowish or dark yellow, with pure dolomite and clouded core structures rarely observed (Figure 1b, e). Dolomite crystals near the dissolution edges exhibit dissolution features, with fine dolomite fragments filling the spaces between the crystals. Some intercrystalline spaces and internal grains are filled with large amounts of dark organic matter (Figure 1c, d), with remnants of bioclastic material present and fractures filled with organic matter (Figure 1f). The parent rock is likely bioclastic limestone. Fine-crystalline dolostone is developed at the foot of the profile and occurs at the bottom of the Qi I section, with a thickness of approximately 6 meters. Dissolution is more pronounced at the top and bottom, and dissolution pores are filled with calcite and black organic matter (Figure 1c, d). The upper part is bioclastic mudstone, while the lower part is a set of fine-grained sandstone from the Liangshan Formation.

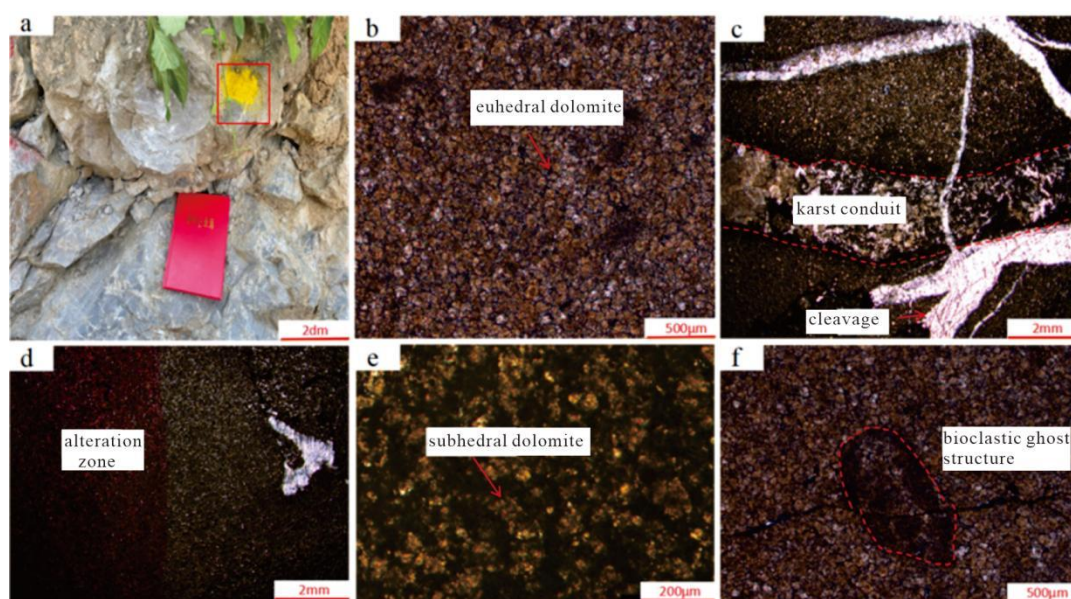


Figure 1. Macroscopic and Microscopic Features of Fine-Crystalline Dolostone

Notes: (a) Field macro, light gray block dolostone with clear calcite veins and numerous small fissures filled; (b) Polarized light, euhedral dolomite, mosaic distribution; (c) Fine-crystalline dolostone under polarized light, calcite X-type cleavage clearly visible, with karst channels, surrounded and filled with black organic matter; (d) Fine-crystalline dolostone under polarized light, half-stained, with red-stained calcite grains scattered between dolomite grains, and dissolution and filling features; (e) Polarized light, dolomite grains in anhedral-subhedral mosaic, generally dirty, with intercrystalline pores; (f) Polarized light, bioclastic remnant ghosts filled with black organic matter in fractures.

4.2. Leopard-spot Dolomitic Limestone

Leopard-spot dolomitic limestone mainly occurs in the middle-upper section of the Qi I Formation. The macroscopic appearance shows the leopard-spotted portions are dolomitized deep gray dolostone, while the surrounding rock is light gray limestone or mudstone, with calcite veins in some areas (Figure 2a, d). The dolomitized sections have a thickness of approximately 30-50 cm, and the dolomitization shapes vary (Figure 2a, d). The fresh surface of the rock exhibits a strong granular texture, resembling sugar crystals (Figure 2b). Under the polarizing microscope, clear boundaries of the dolomitized sections can be observed. The dolomitized areas mainly consist of subhedral to anhedral fine-grained dolomite, with grain sizes around 200 μm . Some pores are filled with black organic matter and bioclastic fragments (Figure 2c). In some areas, the dolomitization is uneven, with the central part of the dolomite grains being stained, while the edges remain unaffected, with the grain surfaces appearing muddy and yellowish-brown (Figure 2e). The dolomitization boundary is not clearly defined (Figure 2f). Additionally, under the microscope, the dolomite content in the mudstone gradually changes (Figure 2g-i), indicating uneven dolomitization.

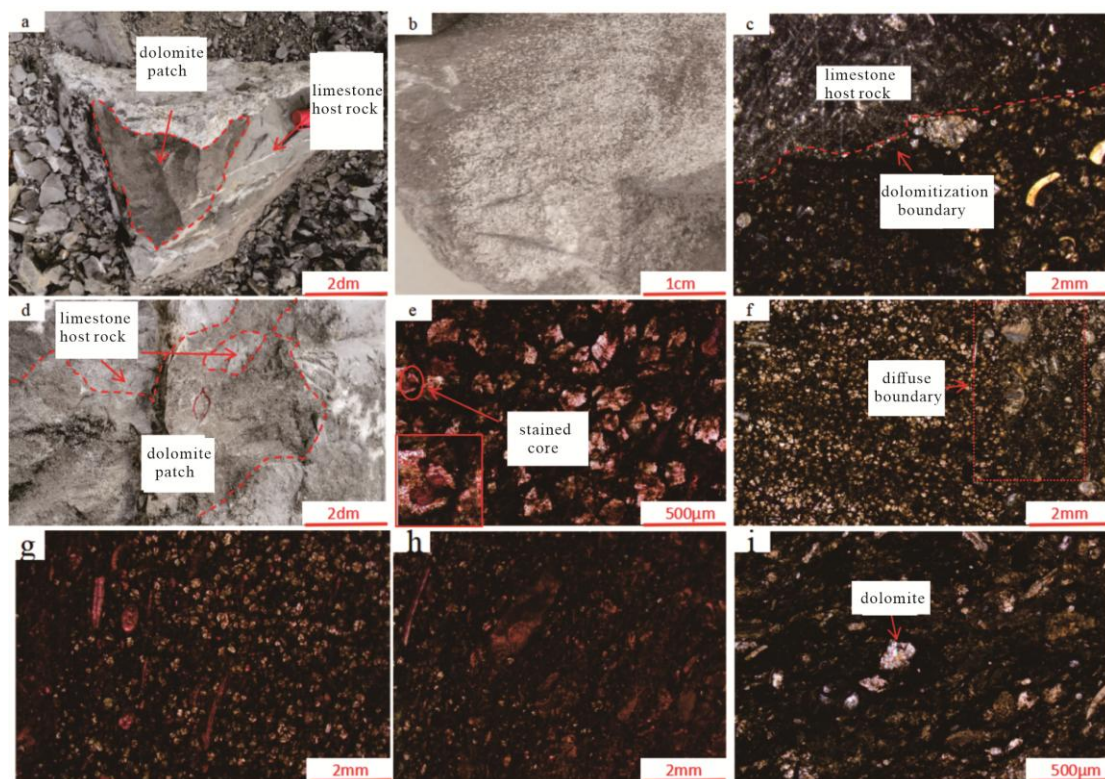


Figure 2. Macroscopic and Microscopic Features of Leopard-spot Dolomitic Limestone

Notes: (a) Field macro, dark gray areas are dolomitized spots, light gray is the limestone surrounding rock; (b) Photo from Figure 2(a), well-dolomitized section with strong granular texture; (c) Photo from Figure 2(a) under polarized light, clear boundary of dolomitization, bioclastic particles present, pores filled with organic matter; (d) Field macro, irregular-shaped dolomitized spots within light gray limestone; (e) Polarized light, half-stained, dolomite grains' cores stained red; (f) Polarized light, unclear boundary of dolomitization; (g) Polarized light, higher dolomite content; (h) Polarized light, reduced dolomite content; (i) Polarized light, only a small amount of fine-grained dolomite.

4.3. Saddle-shaped Dolomitic Cement

In the Huaying Mountain Old Gongqiao Village profile, two types of saddle-shaped dolomite cement are developed in the Qi I Formation. One type is found in siliceous rock, where the boundary between

the silicified black limestone and the white saddle-shaped dolomite cement is clear and easily distinguishable (Figure 3a). Under the polarizing microscope, the saddle-shaped dolomite crystals are mostly crescent-shaped, with curved crystal faces. The crystals are generally euhedral, and the crystal size is coarse, with a mosaic distribution between the crystals (Figure 3b). Under cross-polarized light, the saddle-shaped dolomite exhibits undulatory extinction, while the siliceous material appears blue (Figure 3c). The second type is found in hydrothermal channels, where the saddle-shaped dolomite cement contains limestone clasts. This type appears as a milky white, thin-layered rock with a weaker granular texture than the siliceous rock type, and a stronger greasy texture (Figure 3d, e). The cement near the hydrothermal channel contains dark gray limestone clasts (Figure 3d). Under the polarizing microscope, the saddle-shaped dolomite is generally coarse-grained, with euhedral to subhedral crystals, some of which are fractured and form debris, with fine-grained, irregular-shaped crystals. The crystal surfaces are dirty, and intercrystalline pores are developed, with large pores filled with black organic matter and small particles. Stained limestone clasts can be observed near the dolomite cement (Figure 3f).

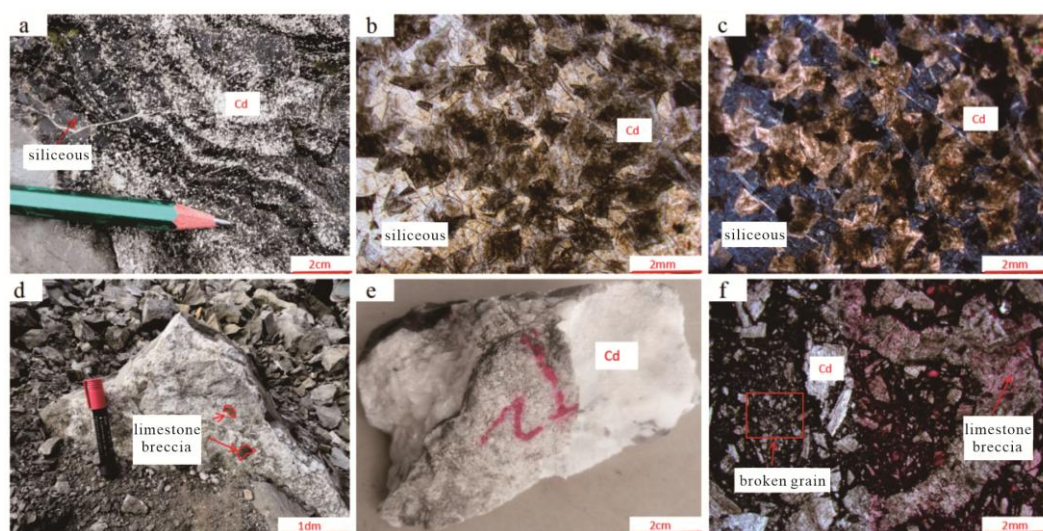


Figure 3. Macroscopic and Microscopic Features of Saddle-shaped Dolomite Cement

Notes: (a) Field macro, black is siliceous material, white is saddle-shaped dolomite cement; (b) Polarized light photo from Figure 3(a), yellowish siliceous material, saddle-shaped dolomite is dirty, embedded in siliceous material; (c) Cross-polarized light, saddle-shaped dolomite exhibits undulatory extinction, siliceous material appears blue, same view as (b); (d) Field macro, hydrothermal channel filled with saddle-shaped dolomite cement and some limestone clasts; (e) Photo from field macro (d), greasy texture; (f) Hand specimen (e) under polarized light, half-stained, with stained limestone clasts near the saddle-shaped dolomite, fractured debris.

5. RESERVOIR SPACE TYPES

5.1. Fine-Crystalline Dolomite

5.1.1. Destruction of topography and landform

A large number of fractures are developed in the dolostone of the Qi I Formation profile. The fractures are mainly tectonic and pressure-dissolution fractures. Most of the fractures are small and short, with lengths approximately 5-20 cm and widths around 0.1-0.5 cm (Figure 4a, b). These fractures are often filled with calcite or black organic matter (Figure 4b). The development frequency of this type of reservoir space is moderate.

5.1.2. Karst Channels

Under the microscope, karst channels are observed in the fine-crystalline dolostone, filled with large amounts of calcite and black organic matter. The development frequency of this type of reservoir space is moderate (Figure 4c, d).

5.1.3. Intercrystalline (Dissolution) Pores

The intercrystalline pores in the fine-crystalline dolostone of the Huaying Mountain Qi I Formation have diameters ranging from 50 to 200 μm . The pores are mostly irregular in shape and filled with black organic matter, with few intercrystalline pores left unfilled. The particle edges are mostly bay-shaped, and the pore types are mainly lamellar and bent lamellar (Figure 4e). These pores represent the primary reservoir space in this type of dolostone.

5.1.4. Cavities

A small number of cavities are observed under the microscope, filled with calcite and black organic matter. The development frequency of this type of reservoir space is low (Figure 4e).

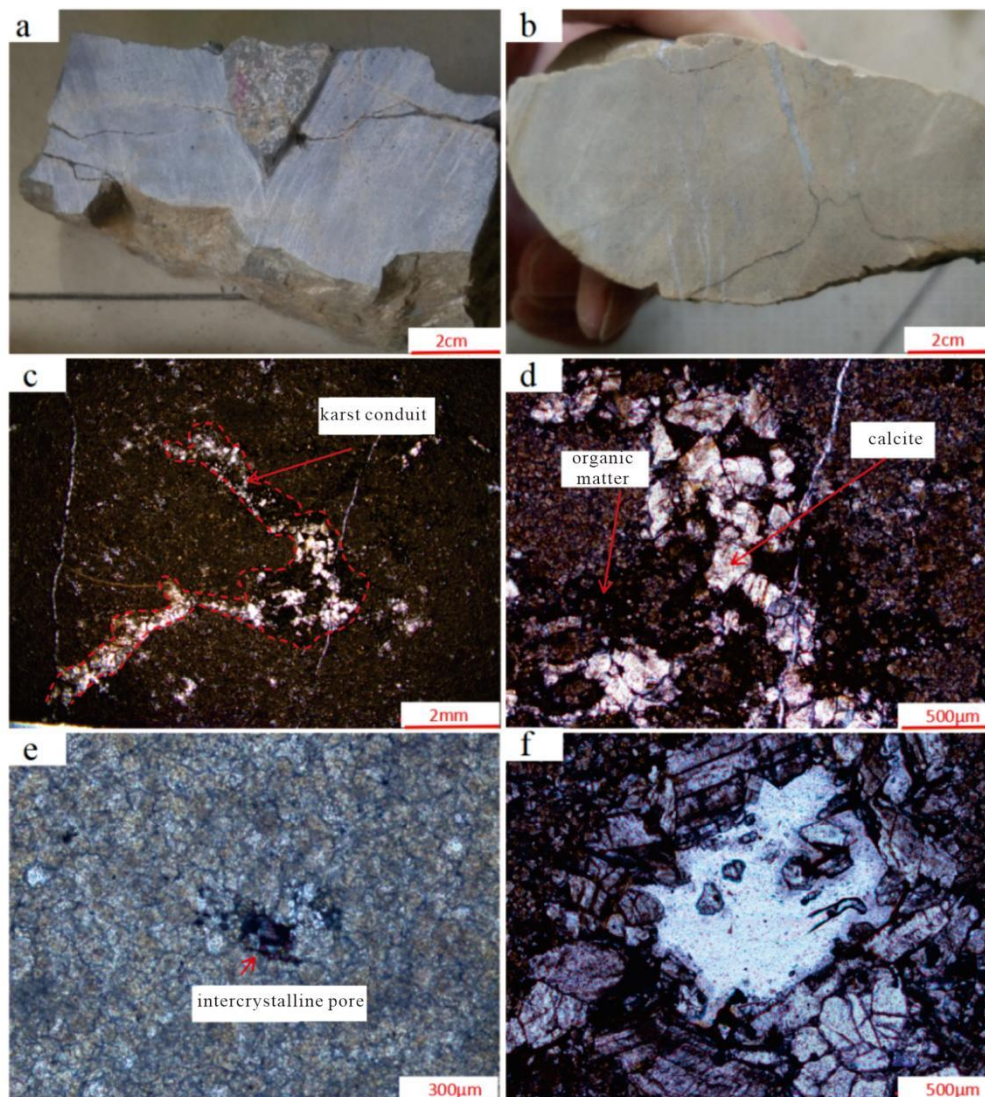


Figure 4. Reservoir Space Characteristics of Fine-crystalline Dolostone

Notes: (a) Hand specimen of fine-crystalline dolostone, showing tiny fractures, unfilled; (b) Hand specimen, fractures filled with calcite and organic matter; (c) Plane-polarized light, karst channels, fractures filled with calcite; (d) Plane-polarized light, magnification of view (c), karst channels filled with calcite and black organic matter; (e) Plane-polarized light, intercrystalline dissolution

pores, bay-shaped edges, filled with black organic matter; (f) Plane-polarized light, cavities filled with saddle-shaped dolomite and black organic matter.

5.2. Leopard-spot Dolomitic Limestone

5.2.1. Fractures

Fractures are more developed in the leopard-spot dolomitic limestone, with sizes that vary. There are large fractures clearly visible macroscopically, some of which are unfilled (Figure 5a), and fine fractures arranged in a straight line (Figure 5b). Under the microscope, fractures are filled with black organic matter and calcite (Figure 5d), found both in the dolomitized and un-dolomitized areas.

5.2.2. Intercrystalline (Dissolution) Pores

The intercrystalline pores in the dolomitized sections are irregular polygons. The boundaries between the dolomite and the voids are relatively straight. The pore diameters range from 50 to 250 μm , with a porosity of about 5%, and they are filled with large amounts of black organic matter. The pore types are mostly lamellar and bent lamellar (Figure 5c). In the un-dolomitized sections, the intercrystalline pores are smaller and harder to observe, located between the fine calcite grains, filled with black organic matter or carbonate mud (Figure 5d). Intercrystalline (dissolution) pores are the primary reservoir space in this rock.

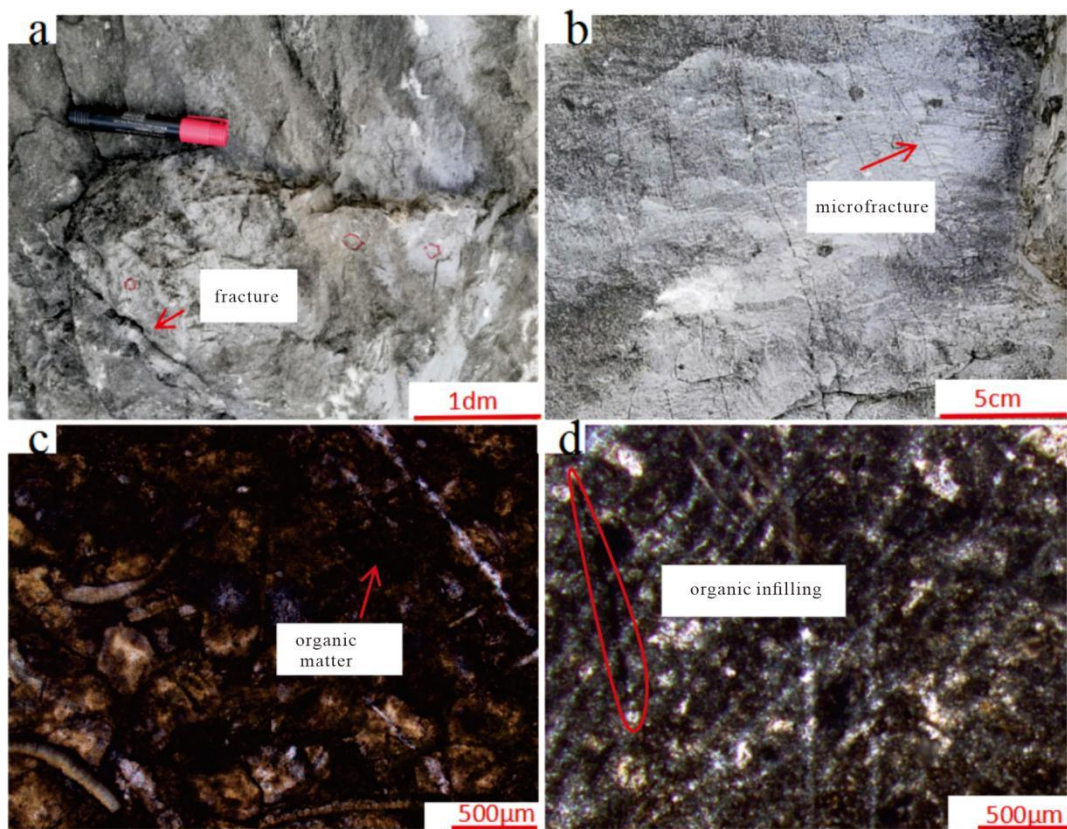


Figure 5. Reservoir Space Characteristics of Leopard-spot Dolomitic Limestone

Notes: (a) Macro photo, large fractures developed; (b) Macro photo, fine fractures arranged in a straight line; (c) Plane-polarized light, intercrystalline pores in the dolomitized section filled with organic matter; (d) Plane-polarized light, un-dolomitized section, fractures filled with organic matter and calcite.

5.3. Saddle-shaped Dolomitic Cement

5.3.1. Fractures

Macroscopically, fractures are developed in the siliceous rock, with fractures filled with calcite (Figure 6a) and small unfilled fractures (Figure 6b). Numerous small fractures are developed in the siliceous rock (Figure 6c). The reservoir space in the hydrothermal channels filled with saddle-shaped dolomite and limestone gravel is not well developed.

5.3.2. Intercrystalline (Dissolution) Pores

Under the plane-polarized light, saddle-shaped dolomite and silica in the siliceous rock show a close contact, with no pores developed (Figure 6c). In the hydrothermal channels, the saddle-shaped dolomite is mostly irregularly aggregated, and some pores are filled with black organic matter (Figure 6d).

5.3.3. Intragranular Dissolution Pores

Under plane-polarized light, large crystals of saddle-shaped dolomite show signs of dissolution and are filled with black organic matter (Figure 6d).

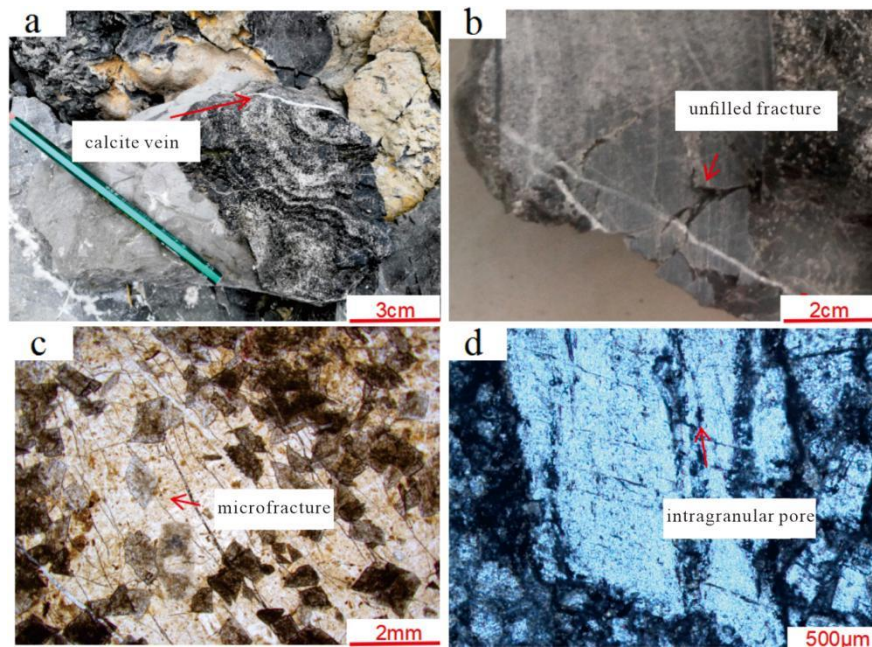


Figure 6. Reservoir Space Characteristics of Saddle-shaped Dolomite Cement

Notes: (a) Macro photo, calcite veins developed in siliceous rock; (b) Hand specimen of siliceous rock, showing small fractures, with visible calcite veins; (c) Plane-polarized light, close contact between silica and saddle-shaped dolomite, small fractures in the silica; (d) Plane-polarized light, large crystals of saddle-shaped dolomite with intragranular dissolution pores, small fractures developed.

6. RESERVOIR PERFORMANCE EVALUATION

In terms of reservoir space, the fine-crystalline dolomite primarily contains intergranular (dissolution) pores, cavities, fractures, and karst channels. Among these, intergranular (dissolution) pores are the most developed and represent the primary reservoir type, while other types of reservoir space have moderate development. In terms of petrophysical properties, the fine-crystalline dolomite is similar to the “yellowish-brown” fine-crystalline dolomite in the central Sichuan’s Moji Gas Field, Jia Lingjiang Formation, which shares similar genesis. Based on the properties of the Lower Jia

Lingjiang Formation reservoir, the average porosity is 3.04%, and the average permeability is $0.01 \times 10^{-3} \mu\text{m}^2$, showing “medium porosity and low permeability” characteristics (Tang Hao et al., 2014). In contrast, the dolomitic limestone with leopard-spot textures has poorly developed reservoir spaces in its limestone matrix (Figure 5d). Only the dolomitic “leopard spots” show a small number of intercrystalline pores and intercrystalline dissolution pores (Figure 5c). Previous studies on the physical properties of the middle-upper Qixia Formation have indicated that the porosity of such rocks generally ranges from 0.47% to 0.82%, with an average of 0.62%, and the permeability ranges from 2.45×10^{-3} mD to 6.66×10^{-3} mD, with an average of 4.55×10^{-3} mD. These rocks are typically classified as poor or non-reservoir rocks (Zeng Deming, 2010).

As for the hydrothermal saddle-shaped dolomite cement, its reservoir performance mainly depends on the physical properties of the original rock it cements. Limestone, as the primary rock being cemented, has an average porosity of less than 1% and extremely low permeability, making it a poor reservoir rock. Furthermore, when karstification and tectonic fracturing, which could improve reservoir properties, are followed by hydrothermal mineral infilling, the reservoir space is significantly reduced.

7. CONCLUSION

(1) The dolomites exposed in the Lao Gongqiao Village profile of the Huaying Mountain are primarily fine-crystalline dolomite at the bottom of the Qixia Formation and spotted dolomitic limestone in the middle-upper part. The fine-crystalline dolomite is light gray and blocky, with dissolution channels filled with calcite and asphalt. Dolomite crystals are predominantly self-formed to semi-self-formed. The spotted dolomitic limestone’s dolomitized parts are light gray macroscopically, with clear or transitional boundaries of dolomitization, indicating an uneven degree of dolomitization.

(2) The fine-crystalline dolomite’s reservoir space is dominated by intergranular (dissolution) pores, with moderate development and poor pore connectivity, exhibiting a “medium porosity and low permeability” characteristic. The spotted dolomitic limestone’s surrounding limestone matrix has almost no developed reservoir space, and the dolomitized portions contain only a small amount of intergranular (dissolution) pores, resulting in poor reservoir performance. The saddle-shaped dolomite, as a hydrothermal filling mineral, reduces the reservoir space and further worsens the reservoir properties.

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