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# Characteristics and Genesis of Carbonate Weathering Crust Reservoirs: A Case from the Ma5Member of Ordovician in Gaoqiao Area, Ordos Basin, China

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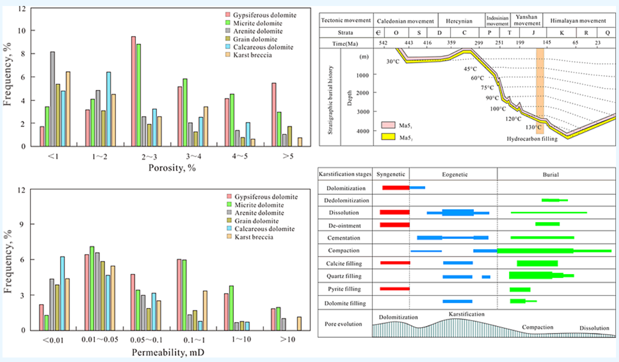
**ABSTRACT:** The hydrocarbon reserves in carbonate rocks account for about half of the global hydrocarbon reserves and are an important reservoir type. The Ordovician Majiagou Formation in the central Ordos Basin is a representative weathering crust reservoir. The Caledonian movement uplifted the stratum as a whole, and subsequently, 120 million years of exposed weathering, denudation, and leaching created this unique karst paleomorphology. Dolomite reservoirs have developed dissolved pores and microfractures, which are the best reserved spaces for natural gas and good hydrocarbon migration channels. This paper takes the Ma5Member (hereinafter referred to as $Ma5_{1+2}$) carbonate reservoir in Gaoqiao Gas Field as the research target, based on the core, thin section, cathodoluminescence, logging data, etc., and systematically study the effect of karstification on the reservoir and the genesis of the dolomite reservoir. The results show that the depositional period of the Ordovician Majiagou strata is a regression cycle and the depositional environment is a limited evaporative tidal flat. The reservoir lithology of $Ma5_{1+2}$ is mainly gypsiferous dolomite and micrite dolomite. The reservoir space types consist of intergranular pores, gypsum mold pore, intragranular dissolution pores, intercrystalline pores, and microfractures. The porosity has values from 0.3 to 11.2% (mostly less than 5.0%) with an average of 3.3%, and the permeability ranges from 0.003 to 13.2 mD (mostly less than 1 mD) with an average of 0.36 mD. Karstification is divided into three periods, including syngenetic karst, eogenetic karst, and burial karst. The sedimentary microfacies determine the material basis of the reservoir, and multistage karstification finally modifies the physical properties. By deeply exploring the formation mechanism and influencing factors of the carbonate reservoir in the Ordovician Majiagou Formation, it provides an important theoretical basis and practical guidance for oil and gas exploration and development. At the same time, it also has important reference value for understanding and predicting the development law and distribution characteristics of carbonate reservoirs under similar geological background.




## 1. INTRODUCTION

Dolomite reservoirs account for about 1/2 of the global carbonate hydrocarbon reservoirs, which is an essential field for future energy development.[1,2] Dolomite can be formed in various periods of diagenesis; with a certain scale of dolomite, its origin often follows a certain pattern. The genetic models of dolomite that have been proposed include osmotic reflux, evaporative pump, burial, hydrothermal, seawater, and mixed water models.[3,4] The genetic model of dolomite is bound up with the sedimentary facies belt, the source of $Mg^{2+}$, and the hydrodynamic mechanism. Dolomite strata have different distribution characteristics under different diagenetic environments and hydrological patterns.[5−8] The depositional environment and dolomitization are closely related to porous dolomite reservoirs, and the effects of later diagenesis in dolomite with different fabrics and mineral compositions are also quite different.[9,10] As a result, dolomite reservoirs typically display diverse lithologies and strong heterogeneous pore systems.[11]

Dolomitization is the main way to form dolomite reservoir and is an important constructive diagenesis.[12,13] Due to the radius of $Mg^{2+}$ is smaller than that of $Ca^{2+}$, a "volume reduction" effect will occur after equimolar metasomatism and the porosity will increase to a certain extent.[14] In addition, under the condition of deep burial, dolomite has stronger resistance to compaction and compression, so it can offset the porosity reduction effect caused by compaction and

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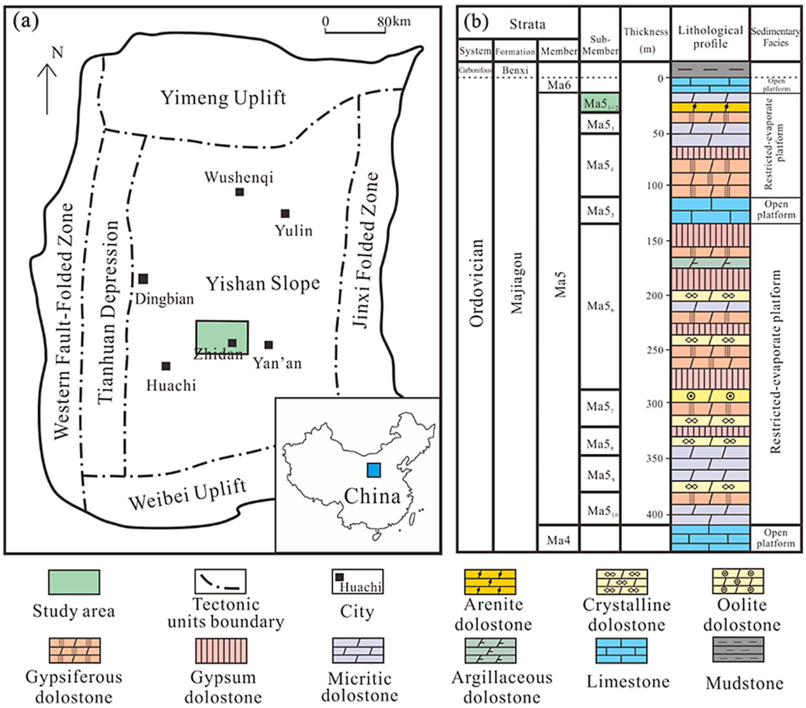


**Figure 1.** (a) Location of the study area and division of tectonic units in the Ordos Basin. (b) Comprehensive strata column diagram of the study area. Studied Majiagou Formation ($Ma5_{1+2}$) is highlighted in green.

cementation, which is beneficial to the preservation of porosity.[15] Recent studies on the genesis of dolomite reservoirs have shown that dolomite can always be formed from matrix dolomite produced by dolomitization, but not necessarily dolomite reservoirs.[16,17] Primary sedimentary facies and early dolomitization are the keys to the development of high-quality reservoirs, and the later tectonic fluid acidification has a vital effect on the formation and maintenance of reservoirs.[18] The formation of good dolomite reservoirs is not only bound to limestone and presedimentary environments[19] but also closely related to porosity evolution during late diagenetic processes.[20,21] Therefore, reservoir genesis is a pivotal geological factor for elucidating maintenance of effective pores and inferring the current pore evolution,[22,23] which is vital for studying the evolutionary process of dolomite reservoirs mechanism, and the coupling relationship with dolomitization provides crucial value.

The Ordos Basin is the second largest hydrocarbon-bearing basin in China. The Ordovician carbonate reservoirs are deeply buried for long sedimentary time and have experienced multistage structural movement and diagenesis transformation.[24] Due to the influence of climate change and paleogeomorphology, the seawater salinity changed periodically during the depositional period, the sedimentary lithology was complex and diverse,[25] and the types and development patterns of different lithologic reservoirs were different, which hindered further exploration.[26] The Lower Ordovician Majiagou Formation is the primary gas-producing interval, which provides an ideal research object for this study. The problems that need to be solved at present are what are the differences and controlling factors of different types of carbonate reservoirs, what rules should the distribution of reservoirs follow, and the genesis of karst reservoirs. In order to verify these problems, based on the methods of core, thin section, physical property test, logging analysis, etc., this paper systematically analyzes the carbonate reservoir characteristics and genetic model of the Ordovician Majiagou Formation and clarifies the genetic mechanism and main controlling factors of dolomite. This work is expected to be applied to the exploration and target selection of a carbonate reservoir in the Ordos Basin and other similar geological conditions.

## 2. GEOLOGICAL SETTING

The Ordos Basin is a craton basin with multitectonic movement, multicycle depression, and multisedimentary environment (Figure 1a). Since the quaternary, the basin as a whole has presented an asymmetrical rectangular basin with a gentle eastern part and a steep western part. There are relatively developed faults and folds on the edge of the basin, but the strata in the basin are gentle and the dip angle is generally less than 1°. According to the present tectonic morphology, the basin is divided into six tectonic units: the Yimeng uplift, the Western fault-folded zone, the Tianhuan depression, the Weibei uplift, the Jinxi folded zone, and the Yishan slope.[27] The study area is located on the Yishan Slope, central Ordos Basin, which is one of the prime areas for natural gas development in recent years.[28]

The Ordovician Majiagou Formation is a representative carbonate formation[26]; according to the characters of lithology, electrical, and marks horizon, the Majiagou Formation is divided into six layers as Ma1 to Ma6Member from bottom to top[29,30] (Figure 1b); at the same time, the Majiagou Formation has experienced three times transgression (Ma2, Ma4, and Ma6Members) and three times regression (Ma1, Ma3, and Ma5Members). The natural gas is mainly stored in the carbonate weathering crust with dissolution pores in the Ma5Member. Based on lithology, sedimentary cycles, and phase sequence characteristics, the Ma5Member can be further segmented into 10 submembers, namely, $Ma5_1$ to $Ma5_{10}$.[31,32] The target strata of this study are $Ma5_{1+2}$.


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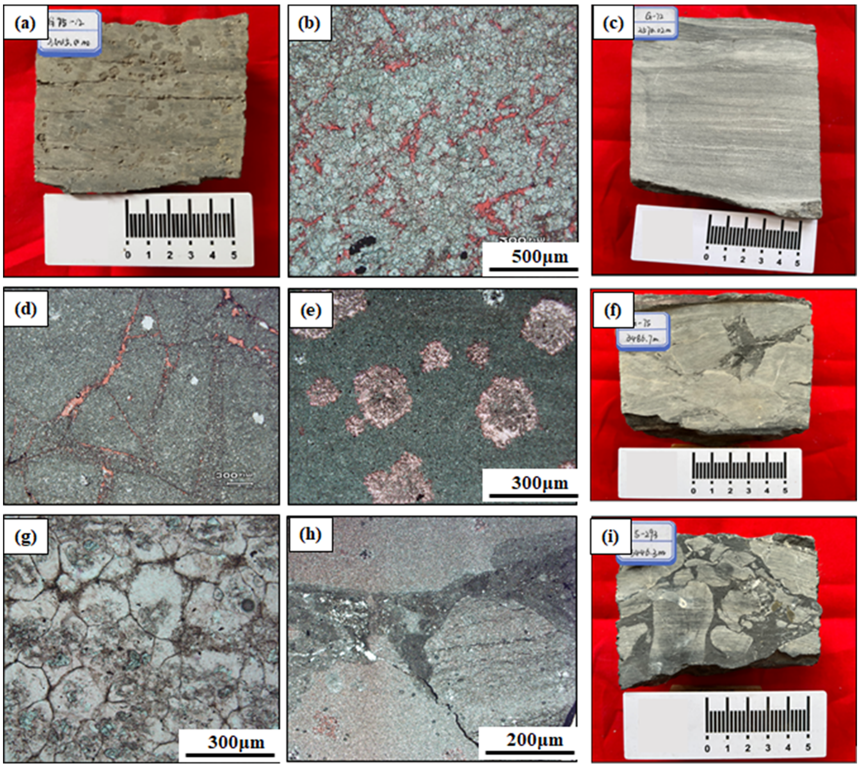


**Figure 2.** Core and thin section characteristics of various types of dolomite. (a) Gypsiferous dolomite retaining numerous gypsum molds and horizontal fractures. Well G-75−12, 3405.4 m, $Ma5_2$. (b) Gypsiferous dolomite in which gypsum is dissolved to form gypsum molds. Well S-340, 3255.8 m, $Ma5_2$. (c) Micrite dolomite, the core exhibits micritic particles with horizontal laminae. Well G-72, 3576.02 m, $Ma5_1$. (d) Micrite dolomite containing visible microfractures. Well G-72, 3577.3 m, $Ma5_1$. (e) Arenite dolomite, in which gypsum molds are partially filled with calcareous cements, undergoes secondary dissolution. Well S-318, 3226.7 m, $Ma5_1$. (f) Arenite dolomite, the vugs are filled with seepage sand and appear gray-black. Well G-75, 3486.7 m, $Ma5_1$. (g) Grain dolomite filled with dolomite particles showing selective fabric dissolution, forming intragranular dissolution pores. Well S-293, 3488.2 m, $Ma5_2$. (h) Calcareous dolomite in which pores are filled with terrigenous clasts and calcareous cements. Well S-292, 3593.1 m, $Ma5_1$. (i) Karst breccia, obvious collapse structure, filled with sediment between breccias. Well S-293, 3446.3 m, $Ma5_1$.

During the late stages of the early Paleozoic era, intense Caledonian movement led to the uplifting of strata. This caused the majority of the Ordos Basin to be deprived of its middle-upper Ordovician sedimentary strata. Also, the Ordovician carbonate rocks experiencing 150 million years of continuous weathering, denudation, and fresh water leaching. As a result, a very special karst paleogeomorphology and weathering crust reservoir were formed, which also created extremely favorable geological circumstances for the accumulation and preservation of large gas reservoirs.[32] The Ma5Member reservoir has been washed and leached by atmospheric fresh water for a long time, and the solution pores have been expanded on the basis of some microfractures or intergranular pores formed in the early phase; the physical properties of reservoir have been further improved. In addition, the favorable conditions of the overlying Carboniferous cap rocks make the Ma5 Formation a favorable area for Ordovician natural gas accumulation.[24]

## 3. MATERIALS AND METHODOLOGY

In this study, 144 samples from 24 exploration wells were selected for laboratory analysis. From 20 November to 14 December, 2021, we performed core description and sampling work in the field, with a total of 144 samples for thin preparation and physical property analysis.

In this study, an Olympus CX23 microscope was used to observe thin slices ($n$ = 144) and count points (250 points per slice) to count the skeleton particles, authigenic minerals, and interstitial materials. The types of pore space, distribution characteristics, diagenetic stages, and the development of dissolved pores were identified. In order to count the preservation and cementation of porosity, the thin sections were impregnated with red-dye resin and cathodoluminescence (CL) testing was performed on 34 typical samples by using a Leica microscope equipped with a CLF-2 CL instrument.

In addition, the porosity and permeability of the samples were analyzed, and the experiment adopts the overburden pressure porosity and permeability measuring instrument PoroPDP-200, working medium for nitrogen, pore pressure set to 1000 psi, and precision pressure sensor for 0.1% of full scale, which fully meet the experiment required accuracy. In the sample analysis involved above, thin section statistics and CL testing were performed at the State Key Laboratory of Northwest University, Shaanxi Province. Physical properties testing was carried out at the Exploration Department of Changqing Oilfield Company, PetroChina.

## 4. RESULTS AND DISCUSSION

**4.1. Petrology.** There are great differences in the rock types formed in different sedimentary environments, and different rock types are also typical of the corresponding sedimentary environments. The observation of cores and thin sections shows that there are mainly six reservoir types in the Ma5Member (gypsiferous dolomite, micrite dolomite, arenite

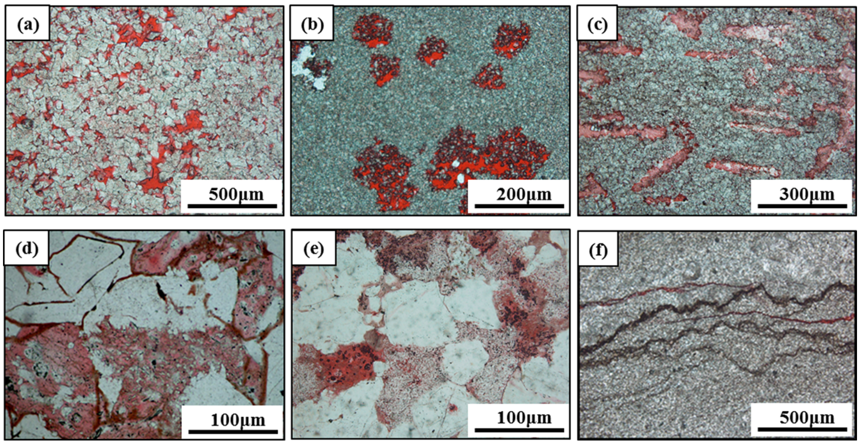


**Figure 3.** Pore types of the $Ma5_{1+2}$ submember reservoir in the study area. (a) Intergranular pore, Well S-300, 3477.8 m, $Ma5_1$. (b) Intergranular pore, Well S-288, 3283.6 m, $Ma5_1$. (c) Gypsum mold pore, Well S-108, 3044.9 m, $Ma5_1$. (d) Intragranular pore, Well S-15, 3539.2 m, $Ma5_1$. (e) Intercrystalline pore, Well S-264, 3442.3 m, $Ma5_1$. (f) Microfracture, Well S-289, 3144.6 m, $Ma5_2$.

dolomite, grain dolomite, calcareous dolomite, and breccia dolostone).

Gypsiferous dolomite is gray-brown in color, dominated by massive structure, and developed high-angle dissolution fractures macroscopically (Figure 2a). During the syngenetic period, the dissolution of gypsum increases the volume and exerts pressure on the bedrock, so a mass of semifilled microfractures can be seen between the gypsum mold pores. This type of rock has the best physical properties in the study area because the gypsum mold pores are widely developed and have good connectivity. Sometimes scattered slat-like gypsum pseudomorphs can be seen, or they are semifilled with seepage silt and calcite (Figure 2b).

Micrite dolostone, mostly gray-black in color, is often developed in the supratidal zone. It is formed by dolomitization of carbonate rocks through evaporation and concentration of seawater. It is a typical contemporaneous dolomite. The content of dolomite is more than 90%, and the bird's eye structure and bedding structure are common on the cores (Figure 2c). It can be seen that calcite and dolomite cement fill the pores and fractures and that there are almost no large dissolved pores. Primary pores and some matrix microfractures are the main pore types of micrite dolomite (Figure 2d).

Arenite dolostone, with secondary grain structure and medium coarse-grained dolomite, is mostly sugar granular, and the grain size is generally more than 0.25 mm, with pinholes and small karst caves (Figure 2e). Under the microscope, the grains are in concave−mosaic contact, and intergranular pores and intergranular solution pores are developed, but most of them are isolated. Dark dissolution spots can often be seen in the core, which are mostly caused by sandy filling (Figure 2f).

Grain dolostones, the particle content, range from 45 to 75%, and the particle size is relatively uniform, mostly between 0.2 and 0.7 mm, and is characterized by particle support (Figure 2g). The sorting and rounding are good, and most of them are subround−round. The dolomite cement of granular dolomite is mainly made up of sand particles and carbonate sand and is mixed with dolomitic mud. The original grain structure was blurred later by strong and thorough dolomitization and recrystallization to show the grain structure. Intercrystalline pores and microfractures are common in this type of rock and are mostly semifilled with seepage silt and authigenic dolomite.

Calcareous dolostones, with a thickness of about 1 m, are loose in texture and very easily absorb water. It is mainly produced at the bottom of $Ma5_1$ and has a stable distribution in the basin area. It is characterized by high gamma, low resistivity, and low density on well logs. Because of its unique lithology and easy to distinguish, it is considered to be the marker horizon of $Ma5_{1+2}$. Calcareous dolomite is mainly caused by dedolomitization due to transient transgressive cycles, and suture structures and horizontal laminae are often seen on cores. The horizontal laminae and pores are often filled with terrigenous clasts and calcareous cements (Figure 2h).

Karst breccia, which is one of the important indicators for identifying the existence of paleokarst, consists of subangular to elliptic gravel, mostly mixed with carbonate mud and sand filling in solution trenches or karst caves (Figure 2i). The breccia with complex composition, different particle sizes, sharp angles, and irregular shape is found in the core.

**4.2. Reservoir Space Types.** Corresponding to various types of reservoir rocks, the Majiagou Formation reservoir space types are also diverse. The reservoir space of the Ma5 member is composed of pores and fractures. The pores include intergranular pores, gypsum mold pore, intragranular dissolution pores, and intercrystalline pores.

Intergranular pores are mainly the original pores formed by the support of the particle structure and can also be the residual pores after the particles are cemented and filled with dolomite. Most of them were formed in the early phases of reservoir deposition. Intergranular pores can be used as seepage channels for pore fluids, laying the foundation for later diagnostic transformations such as dissolution and dolomitization. Intergranular dissolved pores are the products of diagenetic fluid expanding and dissolving along preexisting intergranular pores, which can partially dissolve intergranular cements or matrix, thereby forming dissolved pores with relatively larger pore sizes (Figure 3a,b). Part of the dissolved pores were cemented by calcite and half filled with seepage silt, thus reducing the reservoir performance. Such pores are mainly developed in micrite dolomite and grain dolomite and are one of the main types of pores in the Gaoqiao Gas Field.


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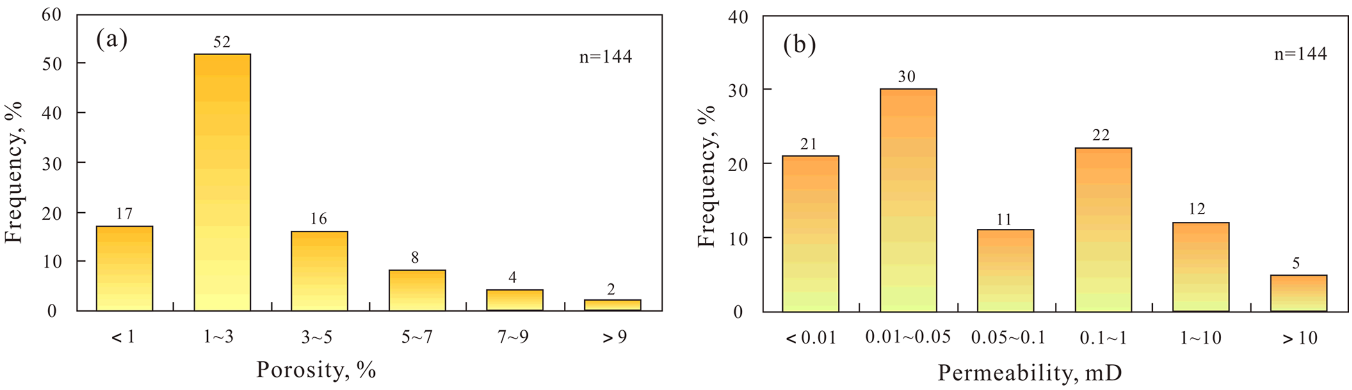


**Figure 4.** Distribution characteristics of porosity (a) and permeability (b) of the Ma5Member.

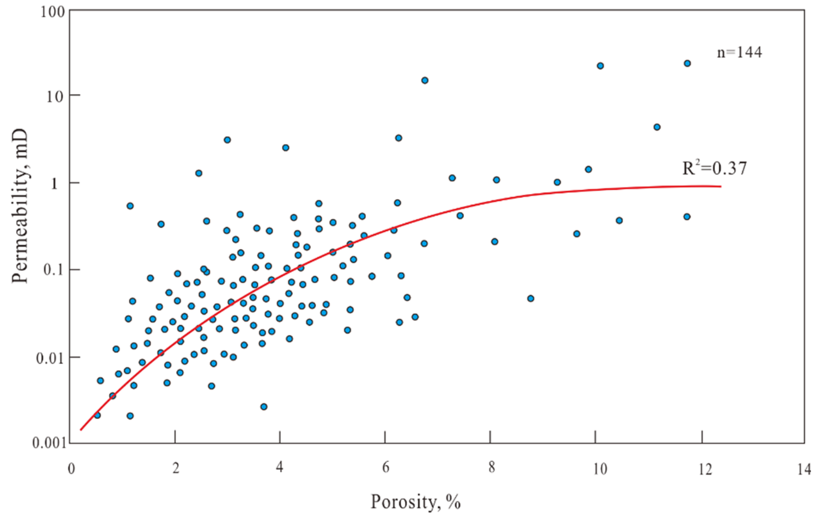


**Figure 5.** Correlation diagram of porosity and permeability of the $Ma5_{1+2}$ submember reservoir.

Gypsum mold pore is mainly formed by leaching of acidic fluid or atmospheric fresh water, which leads to dissolution of gypsum pseudocrystals deposited earlier. This is the best reservoir space type in the area. The external contour of the gypsum mold pore is well preserved, and most of them are regular ellipsoids with pore sizes of about 0.5−1.5 mm, which can be filled by seepage silt and fine-grained dolomite to varying degrees (Figure 3c). This kind of pores can be further dissolved and expanded to form honeycomb-like pores.

Intragranular dissolution pores, which are mainly distributed in the interior of dolomite particles, are formed by selective dissolution of carbonate particles by seawater during the penecontemporaneous period. The shape is irregular, and the pore size is about 0.2 mm (Figure 3d). After that, it can be semifilled by euhedral dolomite and secondary dissolution, forming irregular or fragmentary dolomite filling.

Intercrystalline pores, commonly seen in grain dolomite and arenite dolomite, are formed by dolomitization and recrystallization, with regular shapes and straight edges. Intergranular pores can expand the dissolution area under acidic fluids and form lamellar pores with irregular polygons and pore sizes of 0.03−0.35 mm (Figure 3e). At this time, there will be obvious dissolution traces at the inner edges, and the connectivity between pores is good.

Microfractures are more common in karst breccia, which have short extension and are mostly filled with late dolomite or calcite. Suture lines formed by late dissolution can be seen along the filled fractures (Figure 3f).

**4.3. Reservoir Property.** Through the reservoir property analysis of 144 samples in the Gaoqiao Gas Field, the porosity of more than 80% of samples is less than 5%, ranging from 0.3 to 11.2%, with an average of 3.3%. The permeability of more than 60% of samples is less than 0.1 mD, and the distribution range is 0.003−13.2 mD (mainly less than 1 mD), with an average of 0.36 mD. The physical properties of dolomite reservoir are generally poor, with low porosity and low permeability (Figure 4).

In addition, the cross-plot of the 144 samples shows a weakly positive correlation between porosity and permeability (Figure 5). A small fraction of samples exhibited low porosity and high permeability, mainly related to fractures. Permeability is controlled not only by pore development (size and shape) but also by pore connectivity and fracture development degree.

**4.4. Reservoir Genesis Analysis.** *4.4.1. Sedimentary Microfacies.* The study area is relatively limited to evaporative tidal flat facies, but the reservoir properties of different microfacies are different. According to the relationship between lithology and physical properties (Figure 6), the reservoir physical properties of gypsiferous dolomite and micrite dolomite are generally good, and the distribution of these two types of dolomite is obviously affected by sedimentary environment. The argillaceous dolomite flat is usually located in the underwater geomorphic highland inside


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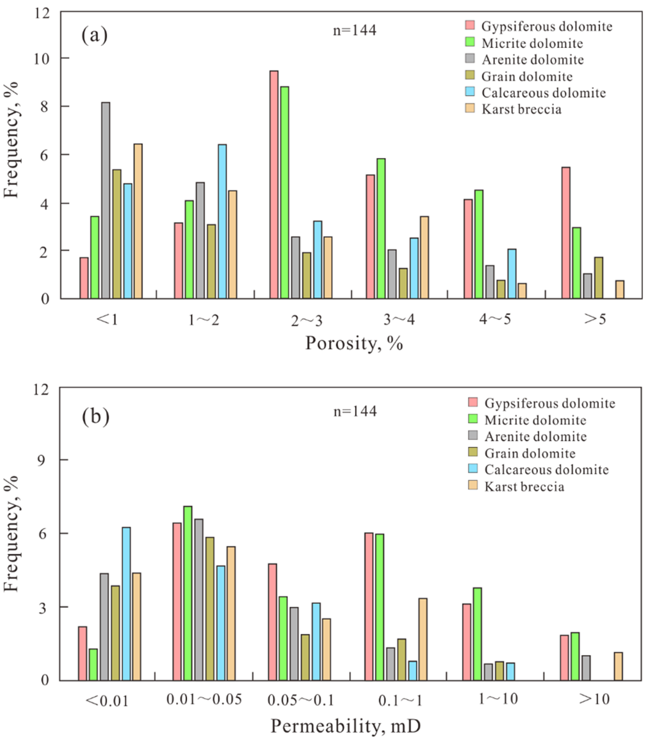


**Figure 6.** Distribution of porosity (a) and permeability (b) of various lithologies in the study area.

the platform, and the depositional interface is in a high-energy environment above the average wave base. The wave scour is sufficient, and the sediments are mainly coarse-grained, with primary pores developed and serving as the seepage channel of the fluid, which is beneficial to the progress of diagenesis such as dissolution and dolomization. Under the influence of late intense multistage karst superimposed transformation, micritic dolomite was eventually formed, with good porosity and permeability and high development degree, which is the most valuable reservoir in the area. Under the influence of continued slow regression and evaporation, underwater terrain highland gradually exposed on the surface, with further evaporation of moisture, the salinity increases, containable space smaller, original materials such as water-soluble gypsum are precipitated, gypsiferous dolomite flat sedimentary environment was born, formed with gypsiferous dolostone, late by karstification and diagenetic evolution, some gypsum mold pore preserved, the reservoir development performance is superior, and the gypsiferous dolostone is the high-quality reservoir in this area.

According to the above analysis, Argillaceous dolomite flat and gypsiferous dolomite flat are dominant facies belts for reservoir distribution (Figure 7), which have high initial porosity and unstable mineral content such as gypsum mass and provide material basis for later karst reconstruction and development of karst reservoirs. Calcareous dolomite flat and mud flat microfacies reservoirs have relatively low porosity and permeability, which is generally not conducive to reservoir development.

*4.4.2. Multistage Karstification.* A set of typical karst reservoirs developed at the middle and upper part of the Ordovician Majiagou Formation in the Ordos Basin, which is characterized by multistage karst transformation. The reservoir has undergone three stages of karst transformation, including syngenetic karst, eogenetic karst, and burial karst (Figure 8).

Syngenetic karst: The occurrence time of karstification is early, accompanied by the relative decline and frequent fluctuation of the sea level, the granular materials in loose or semiconsolidated state are exposed intermittently, and the selective dissolution of unstable aragonite and high-magnesium calcite in carbonate rocks occurs due to seawater immersion, while the insoluble cements between grains occur. The karst of this stage is characterized by selective dissolution of fabric, which often forms dissolved pores in grains, which are relatively isolated. However, the pores formed in the penecontemporaneous period may have laid more favorable conditions for the occurrence of later karstification and become a favorable area for the reconstruction of later karstification.

Eogenetic karst occurs after the deposition of Ma6 strata, which have been exposed to the terrestrial environment for a large area and a long time. Due to the extremely low frequency of mineral grain contacts, the strata are more loosely packed. The carbonate experienced only shallow burial diagenesis and was then lifted to the land, with its buried depth far less than the lower limit of shallow burial depth. Supergene karst mainly represented by a sum of phase alignment syngenetic karst produced a mass of dissolution pores and fractures (Figure 8), along with the continuous cutting, stacking transformation early cave filling period, and into a large number of surface weathering products and black mudstone mixed filling in karst breccia, the core of argillaceous karst breccia, high mud content and filling density, reservoir performance of the early cavern filling section was greatly damaged.

Buried karst: After the Caledonian movement, the thick carbonate rocks of the Majiagou Formation were covered by the Carboniferous and Permian coal-measure strata in the Mesozoic and entered a completely closed diagenetic environment. During the thermal degradation of kerogen in the Upper Paleozoic source rocks, along with the production of high temperature and organic acid fluid, which are dissolved in water to acidify the pore water, the carbonate rocks are dissolved in the fluid to form irregular dissolved pores. This process is carried out on early cementation, followed by secondary filling and cementation during burial. The fillings are mainly coarse-crystalline dolomite, calcite, and a bit of quartz, asphalt, etc. (Figure 9a,b,d,e). Whether effective pores are retained mainly depends on the type of filling and cementation ratio. Dolomite and calcite are commonly found in gypsum mold and intergranular pores. Among them, the filling dolomite has a coarse grain size and a high degree of irregularity and often develops intergranular pores. The filling degree is low, and the damage to the effective pore preservation is relatively small (Figure 9c). On the other hand, calcite has the characteristics of coarse grains due to long formation time span, large temperature change, and continuous growth, and most of the calcite is completely filled in the pores, which is destructive to the reservoir (Figure 9f).

In a word, different transformation stages are affected by sedimentary environment, diagenesis, and tectonics, and their differences are also very obvious. According to the microscopic analysis of cores of different karst types by means of cast wafer, cathode luminescence, and electron microscopy, it can be seen that the karst of the same generation has obvious intergranular dissolution pores and intragranular dissolution pores, most of which are irregular, with unclear edges and varying sizes, and the filling is dominated by microcrystalline calcite. The karst in the supergene period is composed of obvious dissolution holes


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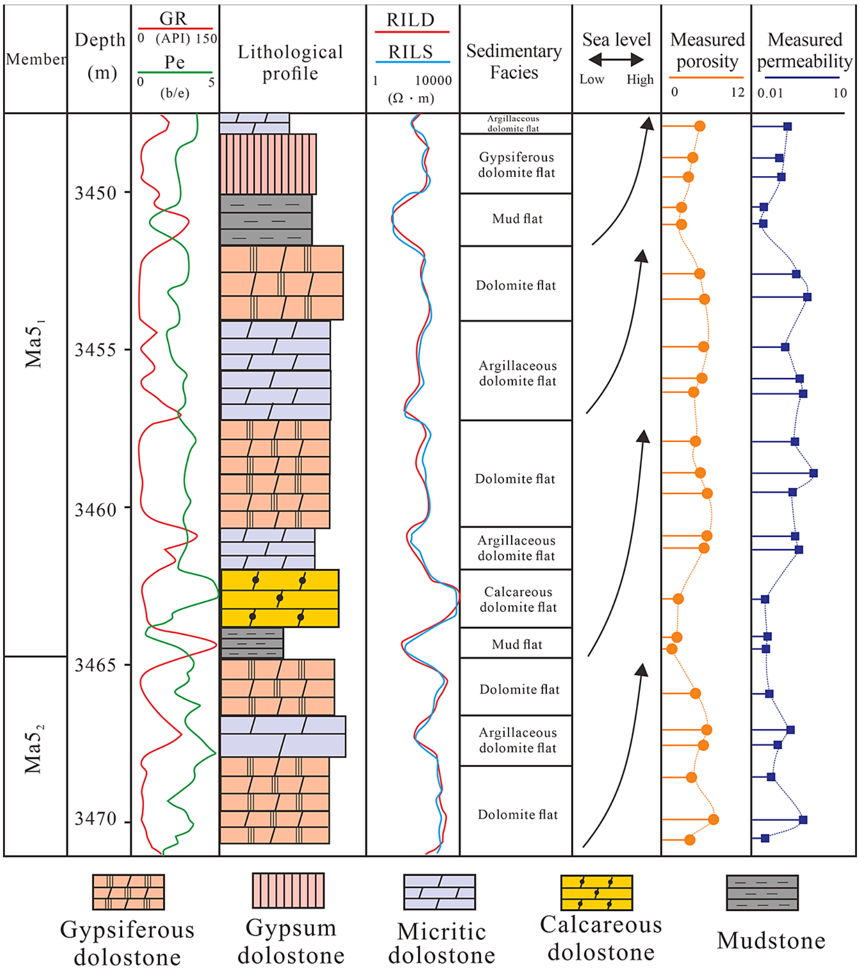


**Figure 7.** Lithologies, physical properties, and sedimentary environment characteristics in Well S-299 in the study area.

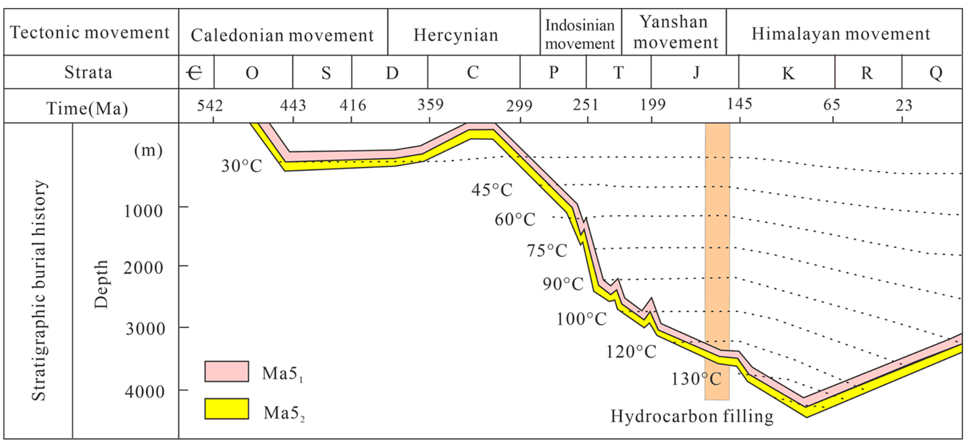


**Figure 8.** History of evaporation tidal flat deposition and burial in Ma $5_{1+2}$ member.

and fractures, mostly in irregular shape, and the filling material is mainly massive or irregular calcite. The buried lava consists of obvious dissolution enlarged pores and intercrystalline pores, most of which are irregular and filled with calcite and dolomite. These differences make the karst process have different geological effects and evolutionary paths in different stages, which have an important influence on the formation and evolution of reservoirs.

*4.4.3. Diagenetic Sequence and Porosity Evolution.* The diagenetic sequence of Member 5 Ma in Gaoqiao area shows a complex process of multistage and multifactor interaction, and its porosity evolution also shows obvious stage changes (Figure 10). From the general trend, the primary porosity dominated the early diagenesis and gradually decreased with the increase of compaction, cementation, and other diagenesis. In the late diagenesis, the secondary pores such as dissolution developed, which played a certain role in compensating the porosity.

In the syngenetic stage, the sediment began to deposit in the diagenetic environment of seawater. Mechanical compaction and early carbonate cementation resulted in a rapid reduction



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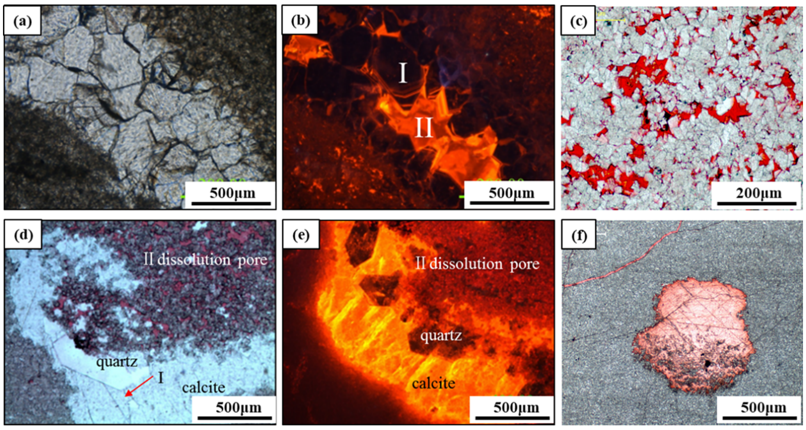


**Figure 9.** (a) Dolomite cements in the dissolution pores. Well S-248, 3330.8 m, $Ma5_2$. Single polarized light (spl). (b) Dolomite cements in dissolution pores, two phases of dolomite are identified; the first phase of dolomite is darker, and the second phase is brighter. Well S-248, 3330.8 m, $Ma5_2$. Cathodoluminescence (CL). (c) Micrite dolostone. Well S-248, 3331.2 m, $Ma5_2$. (d) Quartz and calcite fill in the dissolution pores. Well S-102, 3387.8 m, $Ma5_1$. Cross-polarized light (xpl). (e) Early calcite cement dissolves to form secondary dissolved pores. Well S-102, 3387.8 m, $Ma5_1$. Cathodoluminescence (CL). (f) Micrite dolostone. Pores are filled with a large amount of calcite cement. Well S-102, 3388.4 m, $Ma5_1$.

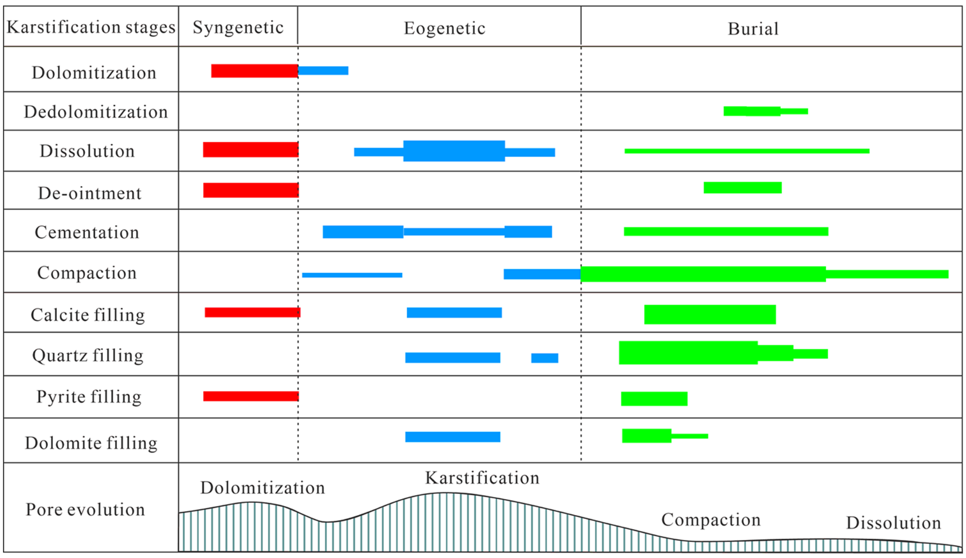


**Figure 10.** Diagenetic sequence and porosity evolution of the Ma $5_{1+2}$ member.

of the primary porosity. At this time, the porosity was high but began to decline. In the eogenetic stage, surface water or atmospheric freshwater functions such as leaching, weathering, and dissolution become dominant. Due to the influence of dissolution, secondary pores gradually develop, but at the same time, due to the influence of mechanical compaction and cementation, the porosity gradually decreases. After entering the burial period, with the continuous thickening of overlying strata, the compaction effect is further strengthened and the pore space in the rock is further reduced. However, at this time, the dissolution in groundwater may become an important factor affecting the porosity again and the development of secondary pores may alleviate the decreasing trend of porosity to a certain extent. Therefore, the porosity may be relatively stable or slightly increased in the late burial period.

## 5. CONCLUSIONS

We present an interpretation of the carbonate reservoir characteristics in the Gaoqiao gas field of the Ordos Basin, China. The study mainly focuses on the petrology, pore space types, and physical properties of the reservoir, aiming to provide a certain geological basis for the genesis of carbonate reservoirs. The major conclusions of this study are summarized as follows:

1. The carbonate reservoirs are an important hydrocarbon reservoir type. The Ordovician $Ma5_{1+2}$ is a limited evaporative tidal flat facies deposit in the central Ordos Basin, the sedimentary lithology is diverse, and gypsum dolomite and micrite dolomite are the dominant sedimentary facies zones. The deposit has experienced three phases of karst successively, i.e., syngenetic karst, eogenetic karst, and burial karst. The structural characteristics and porosity evolution of each stage are different.
2. The reservoir space of the Ma5Member is composed of pores and fractures. Pores include intergranular pores, gypsum mold pore, intragranular dissolution pores, and intercrystalline pores. The average porosity and permeability are 3.3% and 0.36 mD, respectively, which is a classic low-porosity and low-permeability


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dolomite reservoir. Reservoir physical properties (between porosity and permeability) show a weak positive correlation.

3. Dolomite reservoir genesis mainly depends on the transformation degree of sedimentary microfacies and multistage karstification. Argillaceous dolomite flat and gypsiferous dolomite flat are favorable facies zones for reservoir distribution. Multistage karstification effectively transforms the reservoir, which is the key to the formation of high-quality natural gas storage space.

## ■ ASSOCIATED CONTENT

### Data Availability Statement

The data used to support the findings of this study are included within the article. All the data in this article are accessible to the readers.

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### Notes

The authors declare no competing financial interest.

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This research supported by Xi'an Shiyou University Graduate Student Excellent Case Library Project (No. 2023-X-YAL-004). Supergene karst, mainly represented by a series of phase-aligned syngenetic karst features, produced a mass of dissolution pores and fractures (Figure 8). Along with continuous cutting and stacking transformations during the early cave filling period, a large number of surface weathering products and black mudstone mixed into the filling of karst breccia. The core of the argillaceous karst breccia had high mud content and filling density, greatly damaging the reservoir performance of the early cavern filling section.

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