Genesis and pore evolution of dolomite reservoir in the Majiagou Formation, Ordos Basin, China

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Abstract
In gypsum–carbonate rock assemblages, multistage and complex fluids control the formation of dolomite reservoirs that are a focus of hydrocarbon exploration. It is difficult to determine the types of dolomite reservoirs and their formation mechanisms due to the diverse rock assemblages and multiple stages of diagenesis. In this study, we investigated the petrology, reservoir physical properties, and geochemistry of the 6th sub-member of member five of the Majiagou Formation (i.e. Ma56) in the Ordos Basin, China. These data were used to determine the nature and types of gypsum–carbonate rocks, and constrain their reservoir characteristics and diagenetic history, and fluid-related mechanisms that led to dolomite reservoir development and preservation. The Ma56 was deposited on a restricted evaporative platform in the North China Craton, and contains three main types of dolomite reservoirs with variable types of reservoir space. Dolomite reservoir formation was closely related to penecontemporaneous dolomitization, karstification, and differential cementation. Early large-scale dolomitization produced dolomitized carbonate sediments that were resistant to compaction and dissolution, which was conducive to the preservation of primary and secondary pores. The intermittent exposure and dissolution of

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mound–shoal facies sediments, due to high-frequency sea-level fluctuations, was the dominant mechanism for formation of secondary dissolved pores and high-quality reservoirs. During burial, differential cementation occurred due to interaction between fluids and pore size, which determined the extent of reservoir preservation. In general, the studied dolomite reservoirs have undergone multistage diagenesis and alteration, which led to complex and multistage development of the reservoir porosity. However, the reservoir lithology and pore space developed mostly in the depositional to penecontemporaneous stages. Our results provide new insights into the origins of deeply buried dolomite reservoirs in carbonate–evaporite successions.

**Keywords**
Gypsum–carbonate rocks, reservoir genesis, pore evolution, Majiagou formation, Ordos Basin

**Introduction**

Evaporitic and carbonate rock associations are commonly deposited in restricted evaporative settings, and are important hydrocarbon reservoirs worldwide (Hu et al., 2019; Liu et al., 2018). The oil and gas reserves in these types of rocks account for 46.2% of the total reserves in all carbonate rocks (Mu, 2017), and include the Gulf of Mexico Basin in the USA, Abyssal Oceanic Basin in Brazil, Persian Gulf in the Middle East, and Pre-Caspian Basin in Central Asia. These basins contain vast oil and gas reserves, which highlight the importance of conducting research on evaporitic and carbonate rock associations. However, such rock assemblages often experience dolomitization and complex diagenetic processes, which hinder the identification of dolomite types and mechanisms of reservoir formation. For example, gypsum (i.e. anhydrite) is dissolved leaving residual marl due to the action of near-surface meteoric waters (Adams and Diamond, 2017; Xiao et al., 2019a; Zhao et al., 2014). Anaerobic activity of microorganisms means that early low-temperature degradation of such rocks is caused by nitrate reduction, and secondary dissolution is induced by pyrolysis-generated CO2 gas and organic acids during burial (Druckman and Moore, 1985; Hu et al., 2019). Further dissolution can be caused by H2S generated by thermochemical sulfate reduction reactions (Fu et al., 2019; Kotarba et al., 2020; Machel, 2001; Moore and Heydary, 1997; Torghabeh et al., 2021).

The Ordovician strata in the Ordos Basin contain a number of types of evaporite–carbonate rock assemblages. One type is suprasalt that is characterized by the development of gypsiferous nodular dolostone due to karst weathering. Such rocks host the renowned Jingbian gas field (Yang, 1991). Compared with suprasalt, the presalt units are characterized by rhythmically layered gypsum and carbonate rocks, which are located distal from the unconformable surface of the karst weathering surface. Due to the loading effects of the overburden, the presalt unit undergoes completely different sedimentary, diagenetic, and reservoir formation processes than the suprasalt units. In particular, for the Ma57 and Ma59 sub-members, peneconozoic karstification was critical to reservoir formation (Fu et al., 2019; Xiao et al., 2019b). The Ma56 sub-member separates the suprasalt and presalt units, and is considered to be a thick evaporitic rock layer, although it has not been studied in detail. However, several deep wells in the central–eastern part of the Ordos Basin have intersected the Ma56, and demonstrated its exploration potential. This sub-member only contains limited evaporitic strata, and consists of large amounts of gypsum nodule-bearing, rhythmically interbedded evaporitic–carbonate rocks. This complex gypsum–carbonate rock assemblage is relatively unusual and requires further investigation in order to understand the mechanisms of reservoir formation.

As such, we investigated the petrology, reservoir physical properties, and geochemistry of the Ma56 in the Ordos Basin. We use our observations and data to classify the complex gypsum--
carbonate rock types, constrain the reservoir characteristics and diagenetic history, and assess the mechanisms responsible for dolomite reservoir development and preservation. This paper focuses on reconstructing the relationship between the rock assemblages and pore evolution, and presents a model for reservoir formation in complex evaporite–carbonate rock assemblages. Our model also has implications for regional hydrocarbon exploration.

**Geological setting**

The Ordos Basin is located in the western North China Craton, and is a rectangular basin that extends across Shaanxi, Gansu, Ningxia, Inner Mongolia, and Shanxi provinces. The basin has an area of $3.7 \times 10^5$ km$^2$. In the Early Ordovician, a central paleo-uplift formed in the basin due to abrupt subsidence in the adjacent western Helan Rift. The northern Shaanxi depression formed due to the compensatory subsidence in response to the tectonism in the east, while the southwestern depression formed due to extension (Hou et al., 2002; Shao et al., 2019; Zhao and Liu, 1993). The central paleo-uplift controlled the Ordovician paleogeography and distribution of depositional facies (Shao et al., 2019).

The study area is located in the central–eastern Ordos Basin, and structurally, lies across the Yimeng Uplift and Yishan Slope (Figure 1). The study area covers a region that is $1.12 \times 10^5$ km$^2$ in size. Tectonism in the study area resulted in three transgressions and three regressions during deposition of the Majiagou Formation in the Early Ordovician, which generated multiple, complete transgressive–regressive depositional cycles with alternating development of carbonate and evaporitic rocks (Shao et al., 2019). Based on the depositional cycles and lithological associations, the Majiagou Formation can be divided into six members, with the fifth member corresponding to the depositional period during a regression. In addition, secondary depositional cycles are evident in the fifth member, which is further divided into 10 sub-members. The Ma$^5_6$ recorded the largest regression in the member, and was characterized by the deposition of thick gypsum beds along with thin carbonate beds.

**Figure 1.** Tectonic units, well locations, and stratigraphy of the central–eastern Ordos Basin, China.
Samples and methods

This study is based on data from 23 cores of the Ma56 in the central–eastern Ordos Basin. The cores have a total length of about 160 m, and were systematically observed, described, and sampled. The samples were made into thin-sections and stained with alizarin red. Thin-sections were also prepared of samples (n = 150) injected with blue epoxy resin, in order to highlight porosity. Stable C–O isotope and trace element analyses were conducted at the Southwest Petroleum University, Division of Key Laboratory of Carbonate Reservoirs, China National Petroleum Corporation. The whole-rock samples (20 mg in weight) for stable C–O isotope analyses were obtained by microdrilling, and then analyzed in an ultraclean laboratory with a MAT 253 Plus mass spectrometer. The analytical procedure was as follows: (1) a sealed reaction bottle containing the carbonate rock powder was flushed with high purity He gas, injected with phosphoric acid, and held at a constant temperature of 70°C for 1 h; (2) the released CO2 gas was moved by He flow into the mass spectrometer. The data were standardized to V-PDB and have an accuracy of <±0.01‰ (δ13C) and <±0.02‰ (δ18O). For trace element analysis, the samples were embedded in epoxy resin and made into thick-sections. Analytical sites were chosen under a microscope in plane-polarized light and from cathodoluminescence images. The thick-sections were then cleaned by ultrasonication in ultraclean water. Finally, the trace element analyses were undertaken by laser ablation inductively coupled plasma mass spectrometry. The different types of rock fabric were also tested using in situ microbeam analysis technology (Dautriat et al., 2010).

Porosity and permeability analyses were undertaken in the State Key Laboratory of Oil and Gas Reservoir Geology and Development Engineering, Southwest Petroleum University, based on a standard rock porosity and permeability measurement method (SY/T 6385-2016), with an accuracy of ±0.01% for porosity and ±0.005 × 10⁻³ µm² for permeability.

Results

Petrography of the dolomite reservoirs

Lithofacies types. The Ma56 consists mainly of four types of rocks: muddy to micritic dolomite, grain dolostone, microbialite, and gypsum. The specific characteristics of each type are as follows:

1. The muddy to micritic dolomite consists of dolomicrite and micritic dolomite. The former is dark gray in color and dense, horizontally or nonstratified, and contains occasional, isolated pores in gypsum (Figure 2(a)) and salt (Figure 2(b)). The dolomicrite was deposited in a low-energy, restricted setting. The latter is yellowish to gray–brown in color (Figure 2(c)), and has a mosaic texture and ghost particles. The protolith rock was initially doloarenite that was deposited in grain shoal facies above the wave base.

2. The grain dolostone consists of doloarenite (dolorudite) and “granophyric” doloarenite. The former has a clear structure and good preservation, and is particle-supported (60–75% of 0.1–0.5-mm-sized grains; Figure 2(d)) and contains intergranular and intergranular dissolution pores (Figure 3(e)). The latter has an arenaceous texture and is assumed to have formed from doloarenite or arenaceous micritic dolomite deposited in grain shoal facies under high-energy conditions. The “granophyric” doloarenite contains intergranular and intergranular dissolution pores (Figure 3(f)), and some pores are filled with gypsum and silt.

3. The microbialites can be divided into two types: thrombolites and stromatolites. The thrombolites are gray in color, layered, and exhibit cluster structures (Figure 3(a)), cemented granular
structures (Figure 3(b)), and grid textures (Figure 3(c)) under the microscope. Only a small amount of residual lattice pores are visible, as these have been largely filled with agglutinates (Figure 3(c)). The stromatolites typically exhibit bright and dark layers (Figure 2(i) and (j)), in which the dark layers are organic-rich micritic dolomite. The bright layers are mostly brown–gray, muddy to micritic dolomite, with near-parallel and slightly wavy laminae (Figures 2(i) and 3(d)), and some dome-shaped laminae (Figure 2(j)). Both stromatolites and thrombolites require photosynthesis to grow, and thus formed in a high-energy shallow-water environment.

4. The gypsum can be classified as lamellar dolomitic gypsum and nodular gypsum. The former typically contains bright and dark layers (Figure 2(k)). The dark layers are gray–brown dolomicrite. The bright layers are gray–white or gray–brown gypsum that formed in a low-energy and strongly evaporative environment. The layers vary from tens of centimeters to several meters in thickness. The nodular gypsum is light gray and off-white in color, and comprises gypsum nodules of different sizes and shapes set in a dark gray argillaceous dolomite (Figure 2(l)). Nodular gypsum is widely developed in the study area, and formed mostly at the top of the high-frequency cycles in low-energy, shallow-water, and high-salinity conditions where subaerial exposure was common. Each lamina is about ten to several tens of centimeters in thickness.

Depositional sequences. Our petrological observations identified several upward-shallowing sedimentary sequences, and these sequences can be divided into four lithofacies assemblages: dolomicrite–stromatolitic dolostone–doloarenite; dolomicrite–doloarenite–thrombolitic dolostone–stromatolitic dolostone–gypsum breccia; dolomicrite–doloarenite–gypsum breccia; dolomicrite–dolomitic gypsum–stromatolitic dolostone–thrombolitic dolostone (Figure 4).
For the dolomicrite–microbialite–grain dolostone–gypsum breccia (Figure 4(a) to (c)), the lithological change from dolomicrite to grain dolostone reflects shallower water and higher energy conditions. This led to the stacking and migration of mound–shoal complexes, the water body becoming more restricted and saline, and sulfate saturation and precipitation of gypsum-bearing tidal deposits. For the dolomicrite–dolomitic gypsum–microbialite (Figure 4(d)), the lithological change from dolomicrite to dolomitic gypsum reflects normal-salinity seawater during early deposition and increasingly saline conditions during microbialite deposition. This indicates that the microbialites formed mainly in a restricted, shallow marine environment.

Therefore, it is proposed that there were four types of upward-shallowing paleo-environmental sequences in the Ma₅ in the study area: dolomite lagoon–microbial mound facies; dolomite lagoon–grain shoal–microbial mound–gypsum-bearing tidal facies; dolomite lagoon–grain shoal–microbial mound facies; dolomite lagoon–gypsum lagoon–microbial mound facies. Good reservoir rocks,
such as grain shoal and microbial mound facies deposits, typically developed in the middle and upper parts of the upward-shallowing sequences. In addition, the change from carbonate to gypsiferous rocks suggests the climate gradually became more arid and that sea-level was low, which is consistent with the regressional depositional setting of the Ma5. In the restricted evaporatic platform environment, high-frequency cycles led to the rhythmically interbedded gypsum–carbonate rocks that were controlled by the microgeomorphology.

**Pore characteristics and physical properties**

Petrographic observations indicate that the main reservoir rocks in the study area are microbialites, grain dolostone, and muddy to micritic dolomite. The microbialites (47.9% of the studied rocks) have excellent reservoir properties and contain grid (i.e. fenestral), interlayer, and dissolution pores (Figure 3(a) to (d)). The microbialites have an average porosity of 3.93% and an average permeability of $2.09 \times 10^{-3}$ μm². The grain dolostone (22% of the studied rocks) has moderate reservoir properties, and contains intergranular and intragranular dissolved pores (Figure 3(e) and (f)), which may be filled with gypsum and vadose silt. The grain dolostone has an average porosity and permeability of 3.5% and $2.06 \times 10^{-3}$ μm², respectively. The muddy to micritic dolomite contains mainly inter-crystal (i.e. dissolution), gypsum, and salt pores (Figure 3(g) to (i)), which are closely related to the lithofacies types. The micritic dolomite (13.7% of the studied rocks) contains
inter-crystal (i.e. dissolution) pores (Figure 3(g)), and has an average porosity and permeability of 3.04% and $1.78 \times 10^{-3} \mu m^2$, respectively (i.e. good reservoir properties). The dolomicrites contain isolated gypsum pores (9.3% of the studied rocks) and salt pores (5.5% of the studied rocks). The dolomicrites with gypsum pores contain pores that are usually sub-rounded in shape (Figure 3(h)), well-preserved, and not infilled, and have an average porosity of 1.69% and an average permeability of $0.22 \times 10^{-3} \mu m^2$. The dolomicrites with salt pores contain pores that are relatively regular in shape with straight pore edges (Figure 3(i)), and have an average porosity of 1.12% and an average permeability of $0.55 \times 10^{-3} \mu m^2$.

Based on the physical property data, samples with a porosity > 1% account for about 76.5% of the studied samples, and samples with a permeability > $0.01 \times 10^{-3} \mu m^2$ account for about 68.9% of the studied samples. Therefore, the reservoir in the M5 sub-member is of medium–low porosity and permeability.

In Figure 5, it is evident that the reservoir permeability and porosity of the M5 sub-member are somewhat positively correlated. However, some samples with a similar porosity exhibit 2–4 orders of magnitude variations in permeability, and thus the reservoir permeability was likely improved by microfracturing. In general, the M5 sub-member contains mainly porous- and some fracture–pore-type reservoirs.

**Geochemistry**

**Carbon and oxygen isotopes.** The C–O isotope data are shown in Figure 6. The range of $\delta^{13}C$ values in the M5 dolomites is $-2.38$ to $+0.93‰$, with an average of $-0.36‰$, which is similar to the seawater range ($\delta^{13}C = -2.00‰$ to $+0.50‰$) at the time of deposition. $\delta^{18}O$ values range from $-7.49‰$ to $-4.87‰$, with an average of $-7.30‰$. Compared with seawater values

![Figure 5](image_url). Plots of porosity versus permeability for the Ma5 sub-member in the central–eastern Ordos Basin, China. (a) Gypsiferous dolomicrite and salt-bearing dolomicrite. (b) Grain dolostone. (c) Microbialites. (d) Micritic dolomite.
$\delta^{18}O = -6.60\%e$ to $-4.00\%e$) at the time of deposition, most of the dolomite data are more negative. The microbialites have the highest $\delta^{13}C$ values ($-1.52\%e$ to $+0.93\%e$) and $\delta^{18}O = -9.78\%e$ to $-4.88\%e$. The micritic dolomite has $\delta^{13}C$ and $\delta^{18}O$ values of $-2.38\%e$ to $+0.89\%e$ and $-7.97\%e$ to $-5.85\%e$, respectively. The grain dolostone has $\delta^{13}C$ and $\delta^{18}O$ values of $-2.08$ to $+0.01\%e$ and $-9.19\%e$ to $-5.83\%e$, respectively. In summary, data for the muddy to micritic dolomite are similar to those for the grain dolostone.

**Trace elements.** The microbialites are characterized by low Mn (average = 39.29 ppm), high Sr (average = 67.57 ppm), and high Ba contents (average = 2.00 ppm) (Table 1). The grain dolostone has moderate Mn (average = 47.38 ppm), Sr (average = 48.85 ppm), and Ba (average = 1.32 ppm) contents. The muddy to micritic dolomite has high Mn (average = 48.96 ppm), low Sr (average = 33.53 ppm), and low Ba (average = 0.98 ppm) contents.

**Discussion**

**Early dolomitization**

During deposition of the M5 sub-member in the Orдовician in the Ordos Basin, a secondary regression occurred. A hot–arid climate and rifted setting formed a restricted evaporative environment in the central–eastern Ordos Basin (Xiong et al., 2021). In this setting, strong evaporation led to high-salinity and -Mg/Ca seawater, which promoted large-scale early dolomitization (Hardie, 1987; Machel, 2004; Zhao et al., 2014). The dolomite reservoir rocks in the study area (muddy to micritic dolomite, microbialite, and grain dolostone) all preserve original rock fabrics. The microbialite and grain dolostone consist of dolomiticite and muddy to micritic dolomite (Figure 3), with semiidiomorphic crystals, visible bioclasts (Figure 3(c)), and stromatolitic structures (Figure 3(d)).
The Mn/Sr ratios of the different types of dolostone are all <2 (average = 0.79), which means that diagenetic alteration was relatively limited and geochemical information regarding the original fluid is well-preserved (Kaufman et al., 1993; Liu et al., 2020). The Sr/Ba ratios of the different types of dolostone are all >1 (average = 44.03), which are anomalously high and reflect deposition in highly saline seawater (Wang et al., 2021). δ¹³C values of the different types of dolostone are similar to those of Ordovician seawater (Figure 7), indicating that the dolomitizing fluids were originally derived from seawater (Veizer et al., 1999). δ¹³C values of some muddy to micritic dolomite samples are higher than those of Ordovician seawater, which may be related to ¹³C-rich bottom-waters formed by the localized strongly evaporatic and reducing water conditions (Xiong et al., 2020a, 2020b). In summary, the properties of the dolomitizing fluids inferred from the C–O isotope and trace element data are consistent with those proposed in previous studies (He et al., 2014). Most of the dolomites in the M₅ sub-member experienced relatively low-temperature and oxidizing diagenesis, although some dolomites experienced relatively high-temperature and reducing diagenesis. All the diagenetic fluids were marine in origin. Therefore, it is proposed that the dolomites in the M₅ sub-member formed in a subaerial and shallow burial diagenetic

| Lithofacies type            | Sample number | Mn/ppm | Sr/ppm | Ba/ppm | Sr/Ba | Mn/Sr |
|-----------------------------|---------------|--------|--------|--------|-------|-------|
| Microbialites               | T102-2        | 35.15  | 64.05  | 3.26   | 19.64 | 0.55  |
|                             | T102-3        | 34.28  | 70.52  | 0.85   | 82.85 | 0.49  |
|                             | T102-4        | 38.86  | 66.53  | 1.71   | 38.94 | 0.58  |
|                             | T102-5        | 35.55  | 65.69  | 0.94   | 69.56 | 0.54  |
|                             | T102-6        | 37.17  | 61.21  | 2.20   | 27.83 | 0.61  |
|                             | T102-11       | 36.19  | 64.81  | 2.64   | 24.59 | 0.56  |
|                             | T102-13       | 38.76  | 62.89  | 1.23   | 51.13 | 0.62  |
|                             | T102-16       | 33.31  | 71.29  | 1.15   | 62.08 | 0.47  |
|                             | T102-17       | 33.31  | 64.82  | 1.63   | 39.76 | 0.51  |
|                             | T78-4-1       | 42.68  | 82.53  | 2.34   | 35.29 | 0.52  |
|                             | T78-4-3       | 41.47  | 72.41  | 4.36   | 16.61 | 0.57  |
|                             | T78-4-5       | 61.72  | 64.12  | 4.32   | 14.83 | 0.96  |
|                             | T78-4-6       | 41.03  | 63.77  | 1.43   | 44.67 | 0.64  |
|                             | T78-4-8       | 41.85  | 71.56  | 1.71   | 41.89 | 0.59  |
| Grain dolostone             | T78-4-11      | 38.73  | 64.85  | 1.34   | 48.52 | 0.60  |
|                             | T78-4-12      | 38.50  | 70.06  | 0.94   | 74.64 | 0.55  |
|                             | T105-3        | 40.68  | 44.70  | 1.22   | 36.64 | 0.91  |
|                             | T105-7        | 47.44  | 46.26  | 2.18   | 21.24 | 1.03  |
|                             | T105-10       | 46.30  | 52.89  | 1.45   | 36.37 | 0.88  |
|                             | T105-15       | 39.16  | 44.15  | 1.36   | 32.53 | 0.89  |
|                             | T105-23       | 69.50  | 68.08  | 1.88   | 36.16 | 1.02  |
|                             | T105-24       | 47.71  | 46.10  | 1.67   | 27.55 | 1.04  |
|                             | T105-30       | 47.14  | 47.38  | 0.84   | 56.72 | 1.00  |
|                             | T105-31       | 41.31  | 41.90  | 0.99   | 42.33 | 0.99  |
|                             | T105-32       | 47.19  | 50.37  | 0.98   | 51.42 | 0.94  |
|                             | T105-34       | 48.79  | 47.50  | 1.06   | 44.79 | 1.03  |
|                             | T105-35       | 46.02  | 48.00  | 0.88   | 54.46 | 0.96  |
| Muddy to micritic dolomite  | T78-89-5      | 48.07  | 29.62  | 0.42   | 70.60 | 1.62  |
|                             | T78-89-7      | 49.85  | 37.44  | 1.55   | 24.09 | 1.33  |
setting, which was closely associated with high-salinity seawater in the penecontemporaneous stage.

Previous studies have investigated the formation and pore development of deeply buried dolomite reservoirs (Budd, 1997; Fu et al., 2019; Hardie, 1987; Machel, 2004; Warren, 2000; Wu et al., 2016; Zhao et al., 2014). It is commonly thought that the reservoir pores are mainly inherited from primary or secondary pores generated by early dissolution, and that early dolomitization has a key role in the preservation of primary pores. A large number of dissolution experiments have also shown that dolomite is more difficult to dissolve than limestone in subaerial or shallow burial environments (Gautelier et al., 1999; Shen et al., 2016). Therefore, early dolomitization can help preserve primary pores and also change the composition and structure of the initial rock allowing it to resist compaction and pressolution, which further enhances the preservation of primary pores (e.g. intergranular and lattice pores). These pores provide space and migration channels for diagenetic fluids and hydrocarbons (Ehrenberg et al., 2006; Lucia, 2000). In addition, such rocks are prone to (micro-)fracturing because dolomite is more brittle than limestone (Chen and Qian, 2017; Moore, 2001), which enhances the permeability and oil and gas migration.

Diagenetic controls on reservoir quality

Penecontemporaneous karstification and reservoir properties. Although the fifth member of the Majiagou Formation records regressive deposition, high-frequency sea-level fluctuations during deposition of the member occurred (Xie et al., 2020; Xiong et al., 2019). The top of mound–shoal facies deposits in relatively high parts of the depositional setting would have experienced brief exposures to meteoric waters, which formed dissolution pores (i.e. fabric-selective and nonfabric-selective). In the microbialites and grain dolostone, granophytic dissolution is visible (Figure 2(e) and (f)). Grid-like dissolution (Figure 3(a)), intragranular dissolution (Figure 3(b) and (f)), interlayer (internal) dissolution (Figure 3(d)), and intergranular dissolution (Figure 3(e)) pores can be observed. Thus, pores and fractures formed by penecontemporaneous karstification are the main type of reservoir space.

Figure 7. Lithostratigraphy, reservoir physical properties, and depositional cycles of the M5 sub-member in well J5.
δ\(^{18}\)O values (−9.19‰ to −4.87‰) of the dolomite samples are lower than those of Ordovician seawater (−6.60‰ to −4.00‰; Veizer et al., 1999), which probably reflect O isotopic fractionation during burial and heating (Nielsen et al., 2010; Xiao et al., 2020). The δ\(^{18}\)O values of the various types of dolostone, especially the grain dolostone and microbialites, vary widely, which was possibly caused by variable alteration due to interaction with meteoric waters. δ\(^{18}\)O values of some grain dolostone and microbialite samples are obviously lower than those of the dolomicrite and Ordovician seawater, indicating the grain dolostone and microbialites were more strongly affected by karstification. This is consistent with the petrological characteristics of the dissolution pores in these two types of dolomite.

The mound–shoal facies deposits of grain dolostone and microbialites were mainly developed in the middle and upper parts of a single upward-shallowing sequence. However, for a single depositional sequence, the physical reservoir properties gradually deteriorate from top to bottom, which results in “downward-deteriorating reservoir heterogeneity” (Figure 7). This is consistent with the distribution and physical properties of reservoirs controlled by penecontemporaneous exposure and dissolution in many oil and gas basins in China and worldwide (Ma et al., 2019; Xiao et al., 2016; Xiong et al., 2019). This indicates that the development of high-quality reservoirs in the study area was closely associated with penecontemporaneous karstification due to high-frequency subaerial exposure.

Cementation controls on the preservation of reservoir space. In the Ma\(^5\) reservoir, the diameters (D) of primary pores are >125 μm, the ratio of the cumulative cemented pore to the total cemented pore is >65%, and the preserved pore is <11% of the total preserved pore. When D < 125 μm, the preserved pore is >75% (Figure 8). This indicates that the cementation strength of the reservoir pores is closely associated with pore size. Given the occurrence of thin carbonate reservoirs between thick gypsum-bearing units in the Ma\(^5\) sub-member, the study area underwent significant cementation (Figure 9(a) and (b)). This was mainly due to the gradual increase in formation pressure during shallow burial.
A large volume of high-salinity fluids was released from the gypsum–salt layer, entered the adjacent carbonate reservoirs with high porosity and permeability, and precipitated minerals in the early-formed pores. When these high-salinity fluids were released from the relatively dense gypsum-bearing rocks into the high-porosity and -permeability carbonate rocks, the sudden expansion of pore space might have reduced the effective solubility of minerals such as gypsum and carbonates, leading to the preferential cementation infilling of larger pores (Emmanuel et al., 2010; Xiong et al., 2019, 2020). As such, the reservoir has filled large pores and preserved empty small pores. The pore size distribution of preserved pores is closely connected to the primary rock fabric (Figure 9). The preserved pore diameter in the doloarenite is mainly 63–125 μm, and accounts for 46.52% of the total porosity, while in the stromatolitic dolostone is mainly 16–53 μm, and accounts for 67.13% of the total porosity. In addition, cementation during early diagenesis (i.e. prior to compaction) can not only limit compaction and pressure solution, but also form a relatively closed diagenetic system during burial that prevents late diagenetic fluid seepage and transformation, which further preserves the pore space (Liu et al., 2020). Therefore, differential cementation is important in the preservation and distribution of the reservoir space.

**Diagenetic and pore evolution**

The petrological observations and geochemical data show that, after deposition, the Ma₅ sub-member was deposited in a restricted evaporative environment under hot–arid climate conditions.
Due to the gradual evaporation, the seawater salinity increased, and gypsisification affected the sea-floor deposits and gypsum was continuously precipitated (Nasri et al., 2015). The precipitation of CaSO₄ increased the Mg/Ca ratio of the seawater, which was conducive to large-scale, penecontemporaneous dolomitization and dolomite cementation, which developed the lithological framework of the Ma₅ reservoirs. This early dolomitization had an important role in the preservation of primary pores, such as intergranular and lattice pores, and formed secondary pores, such as intercrystalline pores.

2. Diagenesis by meteoric waters in the penecontemporaneous stage: Due to the high-frequency sea-level changes, the tops of the mound–shoal facies deposits in relatively high parts of the depositional setting were repeatedly exposed for short periods of time and subjected to karst transformation by meteoric waters. This formed a large number of irregular, secondary dissolution pores, such as enlarged, intergranular, intragranular, and intercrystalline dissolution pores (Figures 3(a) and (b) and 3(d) to (g)), which constitute the most important reservoir space in the Ma₅ reservoir. These pores are mainly distributed in the middle and upper parts of the upward-shallowing sequence, and are concentrated in multiple thin layers (Figure 7). The meteoric waters dissolved gypsum nodules and cement, and formed pores in gypsum (Figure 3(h)), as well as other secondary pores.

3. Diagenesis during shallow burial in the early diagenetic period and deep burial in the middle–late diagenetic period: With increasing burial depth, compaction and pressure solution gradually...
increased. High-salinity diagenetic fluids derived from the evaporatic rocks flowed into adjacent carbonate reservoir rocks, and caused gypsum, dolomite, and calcite cementation (Jones and Xiao, 2005), which resulted in a decrease in porosity. Given the fluid pressure changes, there was differential cementation, which infilled large pores and preserved small pores, and thus resulted in reservoir heterogeneity. In addition, the regional gypsum rocks generated a closed and highly saline diagenetic environment in the underlying reservoirs (Grunau, 1981; Xiong et al., 2021), which blocked the flow of fluids, allowed the formation fluids to rapidly reach equilibrium, and hindered further dissolution and cementation in the deeply buried dolomite reservoirs. Tectonism formed fractures with different lengths and widths in the laminae, and thus improved the pore connectivity and permeability. However, the basic features of the reservoirs, including the lithologies and type of reservoir space, did not change fundamentally during burial diagenesis.

Based on the depositional setting of the interbedded gypsum–carbonate rocks in the Ma₅₆ sub-member, the diagenetic evolution, and the development and preservation of pores, we propose a three-stage pore evolution model for the grain dolostone (Figure 11). The three stages are the contemporaneous–penecontemporaneous, meteoric water dissolution, and burial stages.

In summary, in the interbedded gypsum–carbonate rocks, porous deposits formed in grain–shoal and microbial mound facies in localized, relatively high-energy environments, in which the primary porosity was >40% (Choquette and Pray, 1970; Fu et al., 2019). During the contemporaneous–penecontemporaneous stage, large-scale early dolomitization favored the preservation of primary pores. However, more than half of the primary porosity was lost due to early compaction and cementation. Subsequently, the reservoir experienced dissolution by meteoric waters, which greatly improved the porosity and permeability of the dolomite reservoirs in the mound–shoal complexes, with an estimated 10–20% increase in porosity. In the burial diagenetic stage, the development of microfractures increased the porosity and permeability of the reservoirs, but the continuous compaction and cementation damaged the reservoir space, leading to a gradual decrease in reservoir porosity to <5% (Figure 10). Therefore, although the Ma₅ reservoir underwent complex diagenetic transformations, the basic framework of the reservoir generally formed in the depositional to contemporaneous–penecontemporaneous stages, and should be categorized as an “early formation reservoir type.”

Implications for exploration

Oil and gas exploration in carbonate–evaporite strata worldwide is based on the conventional viewpoint that the layer between the presalt and suprasalt forms a single and tight, thick seal, which hinders effective oil and gas accumulation. The Ma₅ sub-member occurs between the presalt and suprasalt units in the Majiagou Formation in the Ordos Basin. We have found that the Ma₅ sub-member contains diverse sedimentary rock assemblages in different parts of the Ordos Basin, and consists of gypsum nodule-bearing and rhythmically interbedded evaporate–carbonate rock associations, which differ from the thick evaporitic units in the eastern Ordos Basin. The reservoir was eogenetic karst that was affected by high-frequency sea-level changes. Subaerial exposure and karstification in the early diagenetic stage caused by high-frequency sea-level changes were critical to reservoir formation, irrespective of the rock associations. This observation is of significance to reservoir formation in such carbonate–evaporitic rock associations in the Ordos Basin and worldwide. Given that the Ma₅ sub-member is a typical example of the unit between the presalt and suprasalt units, our results have implication for oil and gas exploration in similar geological settings.
Conclusions

1. The Ma5 sub-member consists of gypsum and salt layers interbedded with thin carbonate rocks, which were deposited in a restricted evaporative platform environment, and are characterized by various types of upward-shallowing sedimentary sequences. The main types of reservoir rocks are muddy to micritic dolomite, grain dolostone, and microbialites. The main reservoir space consists of intercrystalline (i.e. dissolution), intergranular, intragranular (i.e. dissolution), lattice (i.e. dissolution), and fenestral pores, which have formed medium-low porosity and permeability, porous- and fracture–pore-type reservoirs.

2. The formation of the Ma5 dolomite reservoir was closely related to penecontemporaneous dolomitization, karstification, and differential cementation. Large-scale early dolomitization formed
the rock framework for the reservoir, which was conducive to the preservation of primary (and secondary) pores. The development of high-quality dolomite reservoirs was closely linked to the penecontemporaneous karstification, and differential cementation favored pore preservation and resulted in the heterogeneous distribution of reservoir space.

3. After deposition of the Ma5 sub-member, it successively experienced different diagenetic stages, including the contemporaneous–penecontemporaneous dolomitization, meteoric water dissolution, and protracted burial stages. Although the reservoir experienced a complex evolution, the basic framework of the reservoir and pores formed in the depositional to contemporaneous–penecontemporaneous diagenetic stages, indicating it is a type of “early formation reservoir.”

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