Ordovician deep dolomite reservoirs in the intracratonic Ordos Basin, China: Depositional model and Diagenetic evolution

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Abstract
Recent natural gas discoveries indicate that non-karstification-dominated reservoirs exist in the intracratonic Ordos Basin. This study examines the sedimentological and geochemical characteristics needed to clarify the depositional model and diagenetic evolution process of this newly discovered reservoir type. The depositional environment of the dolomite reservoir can be characterized as a tidal flat that grew from the Central Paleo-uplift to the eastern depression by cyclic progradation on an epeiric platform. A tidal flat sequence can extend laterally as a progradational wedge in each cycle of sea level fluctuation. The sheet-shaped peritidal shoal facies associations patched on the wedge represent potential dolomite reservoirs and can be recognized by the presence of doloarenite that has been altered into a vaguely relict grained-texture by diagenesis. Although continuing destructive diagenesis has led to reservoir densification, burial dolomitization and burial dissolution with facies selectivity have tended to occur in peritidal shoal facies associations, thus improving the quality of the dolomite reservoirs. These models provide new insights for targeting deep dolomite hydrocarbon reservoirs in intracratonic basins.

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Keywords
Dolomite reservoir, peritidal sequence, dolomitization, Ordovician Majiagou Formation, Ordos Basin

Introduction
The Ordos Basin, China, is a large petroliferous basin that has been the focus of exploration for many decades, with abundant oil and gas resources successively discovered in the Lower and Upper Palaeozoic and Mesozoic strata (Chen et al., 2017; He, 2003; Liu, 2011; Sun et al., 2009). Currently, it hosts the largest gas fields discovered in China, with reserves of more than $10^{11}$ m$^3$. In 1989, the Jingbian gas field, the first giant karst gas field in China, was discovered in marine carbonate strata of this Basin (Dai et al., 2010; He et al., 2005). The Lower Palaeozoic marine carbonate formations, with a large thickness and extensive areal distribution, have always been regarded as important oil and gas exploration targets (Su et al., 2011). For over 20 years, carbonate exploration has been restricted to the very top of the Majiagou Formation (sub-members M$^5_1$–M$^5_4$). However, recent research has suggested that non-karstification-dominated carbonates could be targeted for gas exploration. It is well known that gas released from the overlying coal measures has migrated into the very tops of the karstification-dominated reservoirs and the upper Palaeozoic sandstone reservoirs (Han et al., 2017; He et al., 2005). Recently, a tectonics-driven coal-derived gas lateral migration model proposed that the lower sub-members (M$^5_5$, M$^5_6$, ..., M$^5_{10}$) situated east of the Central Paleo-uplift may have been charged from the overlying hydrocarbon kitchen (Li et al., 2017; Liu et al., 2015; Miao et al., 2011; Wei et al., 2017; Yang et al., 2011, 2013). Several boreholes have identified gas in non-karstification-dominated dolomite reservoirs far away from the unconformity boundary; for example, a commercially viable gas flow was obtained from sub-member M$^5_5$ in Su 51.

However, controversies related to the depositional model and diagenetic mechanism continue to complicate the prediction strategy for this new reservoir type. There are two competing views on the sedimentary environment model of the Ordovician Majiagou Formation, the platform model (Li et al., 2012; Yao et al., 2008) and the carbonate ramp model (Hou et al., 2003). Several models on the diagenesis of Majiagou Formation have been proposed to illustrate the origin of Majiagou dolomites reservoirs, including seepage reflux dolomitization, burial dolomitization, mixed water dolomitization, and hydrothermal dolomitization (Chen et al., 2012; Feng et al., 1998; He et al., 2014; Hou et al., 2011; Huang, 2011; Li et al., 2016; Ren et al., 2016; Su et al., 2011; Tian et al., 2016; Xia et al., 1999; Xiong et al., 2016; Yang et al., 2006; Zhang et al., 1992; Zhao et al., 2005). However, it remains unclear which of these is most reasonable for interpreting the newly discovered reservoir.

More specifically, the relationship between diagenesis and facies remains unknown, hindering our ability to identify favourable exploration areas. This study examines the petrologic features and sedimentary microfacies of sub-members M$^5_5$ and M$^5_6$ of the Ordovician Majiagou Formation in the Wuqi-Jingbian area of the central Ordos Basin (Figure 1). Samples were characterized using petrography, physical property analysis, temperature measurement of fluid inclusions, X-ray diffraction analysis, C/O isotopes, and logging data. Two models of peritidal sequence formation controlled by the Central Paleo-uplift were evaluated, while the diagenetic evolution and dolomitizations mechanism of the
Figure 1. (a) The paleogeographic map of the Ordovician Majiagou Formation of the North China Block (from Chen, 2010; the studied area marked by the green square, studied boreholes’ sites showing in Figure 4). (b) The location of the Ordos Basin. (c) The lithological column of borehole Lian 14.
dolomitic reservoirs were also considered. Finally, aerial distribution schemes of the facies associations are proposed.

**Geological background**

The Ordos Basin, a secondary tectonic unit in the western part of the North China Craton, is a large multicyclic basin, covering an area of about $37 \times 10^4$ km$^2$. It is bordered by Lvliang Mountain in the east, the Qinling Orogenic Belt in the south, the Helan Mountain-Liupan Mountain in the west, and the Xing’an-Mongolian Orogenic Belt in the north (Chen, 2010; Liu et al., 2009; Zhang et al., 1997). The Wuqi-Jingbian region, in the central Ordos Basin, is located in the middle part of western Yishan Slope (Figure 1).

During the early Palaeozoic, the subduction of Qinling-Qilian paleo-ocean crust caused a paleo-uplift on the southwestern margin of the North China Block. The sedimentary environment was controlled by the Central Paleo-uplift, with an intracratonic epeiric sea located to the east (Figure 1), where an interbedding set of shallow carbonates and evaporites were deposited (Chen, 2010; Deng et al., 2005).

At the end of the Early Palaeozoic era, Caledonian movement caused the entire Ordos Basin to uplift and experience a hiatus of about 150 Ma (Xia et al., 1999). During this period, the top of the Ordovician Majiagou carbonate layers were exposed at the surface where they interacted with meteoric water (Wang et al., 2005). In the Late Palaeozoic, with the sedimentary environment of the basin gradually turning from an epeiric sea to an intracontinental depressional basin, coal-bearing clastic rocks were unconformably deposited over the karstic rocks.

The 5th Member of Majiagou Formation is located to the east of the Central Paleo-uplift and is divided into 10 sub-members from top to bottom based on lithostratigraphic characteristics (i.e., $M_5^1$, $M_5^2$, …, $M_5^{10}$). The upper four sub-members are integrated as the upper karstic part, which has been modified by karstification, while the lower six sub-members are considered to be weakly affected or unaffected by karstification, except for the area of the Central Paleo-uplift. The $M_5^6$, $M_5^8$, and $M_5^{10}$ are evaporites and dolomites formed in a low sea-level environment with a relatively high mud content, while $M_5^5$, $M_5^7$, and $M_5^9$ are composed of dolomites formed in a high sea-level environment with a relatively low mud content. This study primarily focuses on $M_5^5$ and $M_5^6$ as a case (Figure 1).

**Sampling and methodology**

The methodologies employed in this study included observation of cores and geochemical testing of samples. Core observations were carried out at the Xi’an and Qingyang drill core stores of the PetroChina Changqing oilfield. A total of 35 core intervals from 26 wells were observed, and 53 samples were collected. A thin section was prepared for each of the 53 samples, and each was examined under an electron microscope to identify mineral and petrological characteristics. After identifying the facies characteristics from the cores and thin sections, logging electrical characteristics were established for each sedimentary facies, and the logging facies in 26 wells were analysed one by one. Then, facies distribution schemes for both $M_5^5$ and $M_5^6$ were created.

The porosity and permeability, fluid inclusions homogenization temperatures, and degree of ordering of dolomites were evaluated at the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Chengdu University of Technology). Porosity and
permeability were estimated for each of the 53 cylindrical rock samples (Height: 3–4 cm, Diameter: 2.5 cm), and effective porosity and permeability were determined using helium porosimetry and gas permeability. Six thin sections of potential reservoir samples were selected from the 53 samples and prepared for the measurement of fluid inclusion homogenization temperatures, which were determined on a Linkam THMSG 600 instrument. Prior to testing, the textures of the dolomites were identified under the microscope, and seven samples of each type of dolomite (dolomicrites, fine-crystalline dolomites, medium-crystalline dolomites, doloarenites, relict doloarenites, karst breccia dolomites, and dissolved pores dolomites) were selected from the 53 samples. Each 5 g sample was ground to 200 mesh in an agate bowl, and then tested using a D/MAX –IIIC X-Ray Diffraction (XRD) instrument to determine the degree of cation order.

Carbon and oxygen isotopic compositional analysis was conducted on samples of doloarenites and crystalline dolomites. Separation and selection of the individual minerals and their assemblages were done manually from hand specimen or under a microscope. Thereafter, the samples were crushed into particles with a diameter of 0.2 mm and divided into three portions. One portion was used for C/O isotope analyses, and the other two portions were kept in reserve. The C/O isotope analysis was performed at the Analysis and Experiment Center of the Exploration and Development Research Institute, PetroChina Southwest Oil and Gasfield Company. The Finnigan MAT 252 isotope ratio mass spectrometer used in the analysis produced an error of 0.01% for the standard samples specified in the national standard GBW04406.

**Results**

**Reservoir petrologic characteristics**

Core observations and petrographic analysis of thin sections show that the reservoirs in the study area are dominated by doloarenites and crystalline dolomites, whose petrological characteristics are as follows:

a. Doloarenites have a grained-texture, with particle sizes of ~0.02–15 mm, and poor sorting and roundness; grains generally consist of fine-crystalline dolomite (Figure 2(a)). The reservoir primarily contains three type of reservoir space, residual intergranular pores (Figure 2(b)), gypsum-dissolution pores (Figure 2(c)), and dissolution fractures, with corresponding shares of porosity estimated to be 53%, 16%, and 7%, respectively, according to petrographic observation. Transformed by diagenesis, such as dolomitization and recrystallization, the doloarenite has only a vaguely discernible relict grained-texture. Some intergranular pores are occupied by cement. The cement between relict grains often consists of sparite calcite. Two generations of cementation are occasionally observed. The first generation is recognized by granular dolomite coating of particles, and the second by granular calcite filling the pores (Figure 2(a)). Some doloarenites contain irregular and enlarged dissolution pores.

b. Crystalline dolomites mainly include fine-crystalline dolomites and medium-crystalline dolomites with a crystal size of 0.05–0.5 mm, which are the product of doloarenite or micro-crystalline dolomite and formed by dolomitization and recrystallization. Crystals are wheat-berry or rhomb shaped, and some vaguely retain the discernible relict texture of the original particles (Figure 2(d) and (e)). The storage space in this type of reservoir
includes intercrystalline pores (Figure 2(d) and (e)), dissolution pores (Figure 2(f)), and dissolution fractures, with corresponding porosities estimated from thin sections to be 39%, 34%, and 5%, respectively. The intercrystalline pores are regular in distribution; some are formed in gypsum-bearing dolomites and are often filled with crystals of calcite.
or authigenic quartz. Both sides of the dissolution fractures have obvious curved dissolution marks (Figure 2(g)).

**Facies distribution**

Based on the analysis of the lithological features, sedimentary structure, petrologic microfacies, and electrofacies of borehole log data, sedimentary facies distribution schemes for the sub-members M₅⁵ and M₆⁶ were plotted. Many markers of tidal flat facies, such as laminated structures (Figure 3(a)), low-angle and bimodal cross-bedding (Figure 3(b)), and bird’s-eye structures (Figure 3(c)), were found only in cores from boreholes located in the inner side of the Ordovician Central Paleo-uplift. This reveals that the epeiric sea developed a broad zonal tidal flat controlled by the paleo-uplift. It is noteworthy that numerous relict grains of residual doloarenite are present in some thin sections (Figure 3(d)). Owing to dolomitization, recrystallization, and dissolution, the grain structure is not obvious, which may explain why previous studies neglected the importance of relict textures. Doloarenites were found in just four samples (Figure 2(a) and (b)). The grain diameters of doloarenite range widely from about 0.02 to 15 mm. Grains are usually composed of microcrystalline to fine-grained crystalline dolomite. These grains have a moderate degree of sorting and sphericity and are usually cemented by sparry calcite (Figure 2(a)). Only a small number of relict grains are bioclastic dolomite (Figure 3(e)). Observations suggest that these relict grains formed at a peritidal shoal of the epeiric sea, located beside the Ordovician Central Paleo-uplift. A thick layer of gypsum was deposited in an inner lagoon environment of the eastern depression of the Ordos Basin (Figure 3(f)).

The distribution pattern of sedimentary facies association during the two intervals reveal that the sedimentary environment is an intracratonic, semi-restricted, carbonate platform,
with six facies associations: (1) crystalline dolomites associations, peritidal (supratidal + intertidal); (2) doloarenites associations, peritidal shoal; (3) limy dolomites associations, shallow subtidal (external lagoon); (4) gypsum-bearing dolomites associations, shallow subtidal (external lagoon); (5) gypsum-dominated associations, deeper subtidal (internal lagoon); and (6) dolomitic limestone associations, deeper subtidal (internal lagoon). Owing to the sensitivity of depositional environments to sea level fluctuation in the platform geomorphic unit, supratidal and intertidal facies associations interfingered with each other. It is important to note that peritidal is used herein as a general term for these facies associations. The distribution of the associations of the M5\textsuperscript{6} are characterized by north–south-oriented facies belts, consisting from west to east of dolomitic flat patched peritidal shoals, shallow subtidal gypsum-bearing dolomite, and a gypsum-dominated internal lagoon (Figure 4(a)). Owing to sea level rise, the depositional environment of M5\textsuperscript{5} changed to no-evaporate deposition. Facies associations distribute from west to east as dolomitic flat patched peritidal shoals, shallow subtidal limy dolomites, and deeper subtidal dolomitic limestone (Figure 4(b)).

**Reservoir physical properties**

A total of 53 sets of porosity and permeability data were tested, while 59 sets of data were collected from the PetroChina Changqing oilfield. The results indicate that the dolomites of sub-members M5\textsuperscript{5} and M5\textsuperscript{6} have a relatively low porosity, ranging from 0.5% to 8.0%, with a mean of 2.92%, and a peak between 2.0% and 5.0% (Figure 5(a)). Of the samples, 12% range from 5.0% to 8.0% (Figure 5(a)). The permeability of all the samples is between 0.01 and 5.0 mD, and mainly between 0.1 and 0.5 mD (Figure 5(b)).

The physical properties of the reservoir indicate that the dolomites are low porosity and low permeability gas-bearing formations in accordance with the criterion defined by the China National Energy Administration. The relatively highest quality reservoirs occur in doloarenites and crystalline dolomites (Figure 5(c) and (d)). The correlation coefficient
between porosity and permeability is 0.31, which represents a poor correlation (Figure 5(e)), indicating the strong heterogeneity of these reservoirs. The types of microscopic pores in the 53 thin sections were identified and quantified by point-counting (Figure 5(f)). This results show that residual intergranular pores and intercrystalline pores are the primary storage space, accounting for 26.8% and 25.8%, respectively.

**Fluid inclusion homogenization temperatures and the degree of cation order**

A total of six thin sections were selected for measurement of fluid inclusion homogenization temperatures. Homogenization temperatures were successfully obtained from only 25 inclusions identified in four sections. All fluid inclusions are picked from the crystals of matrix dolomite.
The sizes of these fluid inclusions were between 0.2 and 0.3 μm. The minimum temperature was found to be 93.0°C, while the maximum temperature was found to be 123.4°C (Table 1).

The results of X-ray diffraction analysis of seven selected samples of crystalline dolomites and doloarenites show that the degrees of ordering are distributed between 0.65 and 0.92, with a mean of 0.788 (Table 2). Petrographic analyses also demonstrate that most of these dolomites are characterized by fine-crystal sizes and wheat-berry or rhomb shaped crystal faces. The degree of cation ordering in the dolomite lattice is derived from the ratio of the d(105):d(110) superlattice reflection peaks (Fuctbauer and Goldschmidt, 1965; Goldsmith and Graf, 1958). The d(105):d(110) ratios with higher values indicate dolomite with a higher degree of cation order. Although this approach is largely qualitative, it can roughly reflect the texture of dolomite, which in turn is related to its origin.

C/O isotopic composition

In total, 39 sets of C/O isotope data were obtained from the core interval samples that were handpicked from the dolomites (Table 3). The $\delta^{13}$C_PDB values range from −3.43 to 0.5, with a mean of −1.64. The $\delta^{18}$O_PDB values of the rocks vary between −11.22 and −4.84, with a mean of −7.31. As temperature-induced isotope fractionation of $^{13}$C/$^{12}$C seldom occurs, $\delta^{13}$C values can offer information about the sources of carbon in carbonate minerals formed during diagenesis. The $\delta^{13}$C values are similar with those of Ordovician marine facies water (Shields, 2003). Through the temperature-affected isotope fractionation of $^{18}$O/$^{16}$O, oxygen isotopic composition records both temperature conditions and the origin of geo-fluids during diagenesis.

### Table 1. Fluid inclusion homogenization temperatures from the Ordovician Majiagou Formation.

| Well   | Sub-member | The host mineral          | Size (μm) | Gasliquid ratio (%) | Homogenization temperature (°C) | Number of inclusions |
|--------|------------|---------------------------|-----------|--------------------|---------------------------------|----------------------|
| Tao 17-1 | M₅ (3678.32m)| Crystalline dolomite (matrix) | 0.2       | 20                 | 93.0                            | 5                    |
| Su 345  | M₅ (3980.40m)| Crystalline dolomite (matrix) | 0.2       | 10                 | 110.2                           | 9                    |
| Su 379  | M₅ (3811.80 m)| Crystalline dolomite (matrix) | 0.3       | 5                  | 123.4                           | 6                    |
| Su 379  | M₅ (3817.00 m)| Crystalline dolomite (matrix) | 0.2       | 5                  | 106.5                           | 5                    |

### Table 2. X-ray diffraction results for dolomites from the Ordovician Majiagou Formation.

| Sample number | Lithology                  | Sub-member | Degree of ordering |
|---------------|----------------------------|------------|-------------------|
| Su 345-1      | Fine-crystalline dolomite  | M₅         | 0.72              |
| Su 345-2      | Doloarenite                | M₅         | 0.75              |
| Su 127-1      | Fine-crystalline dolomite  | M₅         | 0.81              |
| Su 379-6      | Doloarenite                | M₅         | 0.70              |
| Su 379-7      | Doloarenite                | M₅         | 0.76              |
| Su 379-8      | Medium-crystalline dolomite| M₅         | 0.86              |
| Lian 30-9     | Medium-crystalline dolomite| M₅         | 0.92              |
Table 3. Summary of $\delta^{13}$C and $\delta^{18}$O geochemistry of dolomites.

| No. of specimen | Occurrence | Type of specimen | Specimen sorting                          | $\delta^{13}$C ($^\circ$/oo) | $\delta^{18}$O ($^\circ$/oo) |
|----------------|------------|-----------------|-------------------------------------------|------------------------------|-------------------------------|
| Tao17-1        | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -0.89                        | -6.49                         |
| Tao17-2        | Matrix     | Doloarenite     | Handpicked from hand specimen              | -1.18                        | -5.42                         |
| Tao17-3        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -3.44                        | -8.34                         |
| Tao17-4        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -0.62                        | -7.05                         |
| Tao17-5        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -0.54                        | -7                            |
| Tao17-6        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -0.65                        | -7.46                         |
| Tao17-7        | Matrix     | Fine-crystalline dolomite | Handpicked from thin section               | -0.5                         | -4.84                         |
| Tao17-8        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.39                        | -7.06                         |
| Tao17-9        | Matrix     | Medium-crystalline dolomite | Dolomite handpicked from hand specimen     | -1.83                        | -7.2                          |
| Tao17-10       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.49                        | -11.22                        |
| Su127-1        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.71                        | -6.73                         |
| Su127-2        | Matrix     | Fine-crystalline dolomite | Handpicked from thin section               | -2.02                        | -6.42                         |
| Su381-1        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -2.06                        | -8.31                         |
| Su381-2        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.54                        | -7.14                         |
| Su345-1        | Matrix     | Fine-crystalline dolomite | Handpicked from thin section               | -1.35                        | -7.14                         |
| Su345-2        | Matrix     | Doloarenite     | Handpicked from hand specimen              | -1.22                        | -7                            |
| Su345-1        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.1                         | -8.17                         |
| Su379-1        | Matrix     | Crystalline dolomite | Handpicked from hand specimen              | -1.42                        | -6.63                         |
| Su379-2        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.41                        | -7.12                         |
| Su379-3        | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -3.21                        | -7.11                         |
| Su379-4        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.63                        | -7.12                         |
| Su379-5        | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -2.11                        | -7.48                         |
| Su379-6        | Matrix     | Doloarenite     | Handpicked from hand specimen              | -1.82                        | -8.47                         |
| Su379-7        | Matrix     | Doloarenite     | Handpicked from hand specimen              | -1.62                        | -7.2                          |
| Su379-8        | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -2.41                        | -9.8                          |
| Shan389-1      | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.13                        | -7.42                         |
| Shan371-1      | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -2.93                        | -8.71                         |
| Shan371-2      | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -1.02                        | -8.71                         |
| Lian14         | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -2.61                        | -8.2                          |
| Lian28-1       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.1                         | -6.91                         |
| Lian30-1       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.92                        | -6.73                         |
| Lian30-2       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -2                           | -7.31                         |
| Lian30-3       | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -1.8                         | -7.01                         |
| Lian30-4       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.51                        | -6.41                         |
| Lian30-5       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.42                        | -6.9                          |
| Lian30-6       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -1.33                        | -5.21                         |
| Lian30-7       | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -2                           | -6.92                         |
| Lian30-8       | Matrix     | Fine-crystalline dolomite | Handpicked from hand specimen              | -2.41                        | -8.53                         |
| Lian30-9       | Matrix     | Medium-crystalline dolomite | Handpicked from hand specimen              | -1.76                        | -6.29                         |
Discussion

Depositional models and constraints on reservoir spatial distribution

From our analysis, we conclude that these new gas plays are lithological dolomite reservoirs, and that sedimentary facies association is one of the main controlling factors in their distribution. As previously mentioned, there are two competing hypotheses regarding the use of sedimentary environments for interpreting the Ordovician Majiagou carbonate rocks, namely the platform facies model (Li et al., 2012; Yao et al., 2008) and the carbonate ramp facies model (Hou et al., 2003). The former classifies the sedimentary environment of Ordovician Majiagou Formation as a carbonate platform because of the lithology dominated by shallow dolomites and evaporites. Critics argue that there is no shoal or reef to support development of marginal facies association, which is an essential unit of rimmed platforms. The argument further suggests that evaporates were formed by the concentration of seawater in deep depression basins, but were not deposited on a carbonate platform. Before 2010, companies attempted to identify new carbonate gas reservoirs types (i.e., types other than the karst reservoir discovered in 1989). Guided by the former model, nearly all exploration strategies targeted marginal platform facies associations at the westernmost and southernmost parts of Ordos Basin, with the latter the least likely to result in the discovery of a new type of reservoir. As mentioned above, new indications of potential gas plays have been discovered in recent years. There is now a new interpretation for facies associations of these potential reservoirs under the modified platform model, which asserts that there are marginal facies associations controlled by hypothetical rift troughs that cut into the Ordos intracraton (Fu et al., 2017).

This study focused on microfacies of the Ordos Majiagou Formation. Based on the results, we propose a new model that supports the use of exploration away from the marginal platform, where oil companies have undertaken decades of exploration; instead, the

![Figure 6. Depositional model of the Ordovician Majiagou Formation with a peritidal shoal on the east side of the Central Paleo-uplift.](image-url)
focus should be on intracratonic basin exploration, where potential reservoirs are doloarenites and crystalline dolomites in the peritidal facies associations (Figure 6). Owing to the geomorphologic barrier island formed by the paleo-uplifts, the intracraton corresponded to a semi-restricted epeiric carbonate platform with medium hydrodynamic conditions, developing an extensive tidal flat and a large salt sag (Chen et al., 2017). The salt sag was far from the open ocean owing to the centripetal concentration of sea water. Tidal flats formed on the inside ramp of the Central Paleo-uplift. Owing to moderate topography in the intracraton, sea level changes would result in a long-distance migration of the shoreline. In contrast to the tidal flats of continental margin seas, epeiric sea tidal flats are relatively weak in energy and do not form high-energy linear tidal channel flows. Rather, extensive planar tidal bore surges towards the inside ramps result in widespread tidal flats on epeiric platforms. The tidal flat has a regular distribution of facies belts, which is of great significance in potentially revealing the development of dolomite reservoirs. Tidal bores with flow energy in intertidal zones could give rise to sheet or lens-shaped peritidal shoal deposits. The potential reservoir not only occurs in the shoal facies but should also include the surrounding dolomites.

Based on analysis of the spatial distribution of facies, a sequence-aggradation model of Majiagou formation was proposed, suggesting that the tidal flat would develop a progradational wedge controlled by sea level (Pratt et al., 1992). In each cycle of sea level fluctuation, the tidal flat facies association grew from inside of the Central Paleo-uplift to the eastern depression by progradational patterns, forming a shallowing-upward sequence (Figure 7). The tidal flat progradational wedges are a response to continuous offlap. The lower part of a wedge in the vertical time-sequence is primarily composed of subtidal deposits, whereas laminated intertidal-supratidal deposits occur above. Under the relatively stable hydrological conditions, a lateral extension of all the shallowing upward tidal flat progradational wedges might exceed 100 km and ceased when sea level rose in the next cycle. A new

Figure 7. Sequence and model of the tidal flat progradational wedge. (a) The depositional process of tidal flat progradation wedge, (b) The sequence of tidal flat progradation wedge.
progradational wedge developed, overlapping the former one. Sheet or lens-shaped peritidal shoals developed on the progradational wedges. Peritidal shoal facies associations are different in hydrodynamic conditions of formation and development scale from that of the platform margin and have indistinct responses in seismic and log data, which led to targeting difficulty. Moreover, due to dolomitization and recrystallization, most grains of doloarenite of peritidal shoal facies associations have been converted to crystalline dolomite, which is easily overlooked in petrographic analysis. Grains with relict texture can be vaguely discerned in some doloarenites, which provides evidence for the identification of peritidal shoal facies associations.

**Diagenetic evolution process of the dolomitic reservoirs**

The distribution of potential dolomite reservoirs is controlled by peritidal shoal facies associations. Based on reservoir physical properties, high-quality reservoirs in the study area primarily occur in the relict doloarenite and crystalline dolomite associations. This new type of reservoir is tighter than paleo-karst-dominated reservoirs, with porosity ranging between 5% and 8%. Dolomitization is one of the important diagenetic factors for the dolomite reservoir (Hardie, 1987; Huang, 2010; Machel, 2004; Warren, 2000; Zhang et al., 2010). As discussed, several models have been proposed to interpret the origin of the Majiagou dolomites. While it is known that the dolomites experiences multi-dolomitization, the effects of the diagenetic evolution process are unclear. In addition, the primary type of dolomitization must be selected for the new reservoir type.

We attempted to reconstruct the diagenetic process. Diagenetic minerals were detected through petrographic analyses in thin sections. The mineralogy indicates that diagenesis mainly included dolomitization, dissolution, compaction, pressolution, cementation, recrystallization, and replacement. The occurrence of diagenetic products suggests that the reservoirs have undergone five diagenetic stages: (1) penecontemporaneous; (2) early phase diagenesis; (3) exodiagenesis; (4) medium-phase diagenesis; and (5) late-phase diagenesis. The evolution processes of diagenesis and the estimated porosity were reconstructed from thin sections to determine the textural relationships and volume fractions of authigenic minerals and relative time. According to the estimated volume of the diagenetic products in each stage, a deductive model was proposed to illustrate the porosity evolution process, with the porosity results from this study as the empirical basis. The burial history and the homogenization temperature also provide a basis to reconstruct this model (Figure 8).

(a) In the syngenetic-penecontemporaneous stage, the first generation of calcite cementation coated the grains by marine diagenesis. Then, penecontemporaneous dolomites formed under seepage reflux dolomitization (Su et al., 2011), which can protect the primary intergranular pores of peritidal shoal rocks. The original porosity of the doloarenite is generally around 35% (Beard and Weyl, 1973; Guo et al., 2014; Scherer, 1987).

(b) In the eodiagenesis stage, before the top of the Majiagou Formation suffered exposure weathering, the burial depth of sub-members M5 and M6 was approximately 500 m, resulting in compaction, pressolution, and a high occurrence of second-generation calcite cementation (Figure 2(a)). According to the empirical compaction curve (Pal et al., 2014; Schmoker and Halley, 1982), porosity can be reduced by 8% during this normal burial process (Guo et al., 2014). The mean volume fraction of the second-generation cement was estimated from thin sections to be 7%. These two destructive factors caused a significant decrease (15%–20%) in the intergranular porosity. Referring to the method of intergranular
volume-cementation plotting (Houseknecht, 1987), compaction and cementation of the Ordovician rocks played nearly equivalent roles in reducing porosity.

(c) In the late Ordovician to middle Carboniferous, the crust of Ordos Basin underwent uplift influenced by Caledonian tectonic movement; exodiagenesis continued for around 150 Ma. As a result, carbonate strata at the top of the Ordovician were exposed at the surface, and experienced epidiagenetic karstification. In the study area, sub-members M5<sup>5</sup> and M5<sup>6</sup>, although often over 100 m away from the weathering crust, suffered weak karstification locally with gypsum solution pores (Figure 2(c)) and fractures. Dolomitic breccia formed by karstification can be found occasionally (Figure 2(h)). The porosity could have been increased to 25% under the karstification. Some dissolution pores formed in this period and have been preserved, allowing porosity to be estimated from thin sections directly.

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![Diagram](https://via.placeholder.com/150)

**Figure 8.** Diagenetic evolutionary process of the dolomite reservoir of the Ordovician Majiagou Formation.

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| Diagnostic environment | Burial history (Gao et al., 2014) | Types of diagenesis and diagnostic products | Porosity evolution process (%) | The micrographs of pore and diagenetic phenomena |
|------------------------|----------------------------------|-------------------------------------------|-------------------------------|---------------------------------------|
| Fine-grained sandstone | 400-800 m | Dissolution, Productive | 20 | Pore corrosion at dolomitic dolomite, dolomite, and calcite (M5<sup>5</sup>) |
| Clean sandstone, siltstone | 500-1500 m | Recrystallization, Productive | 30 | Grain dolomite, first generation dolomite (M5<sup>6</sup>) |
| Poorly sorted detrital sandstone | 1500-2500 m | Metasomatism, Plasmatic | 40 | Grain dolomite, secondary generation dolomite (M5<sup>6</sup>) |
| Interbeds | 2500-3500 m | Cementation, Productive | 50 | Grain dolomite, product formation dolomite, well Su 379 (M5<sup>6</sup>) |
| Organic-rich siltstone, minor shale | >3500 m | Permomineralization, Productive | 60 | Grain dolomite, product formation dolomite, well Su 379 (M5<sup>6</sup>) |

Ellipse: Length represents duration, width represents strength. Dashed: represents may or may not occur. The green represents the constructive diagenesis, the red represents the destructive diagenesis.
(d) In the medium diagenetic stage, during which burial depth increased, compaction and pressolution became dominant (Figure 2(l)). A 10% reduction in porosity was calculated according to the empirical compaction curve, which led to a decrease in porosity of about 15%.

(e) In the early late-diagenetic period, the burial depth exceeded 3500 m. The burial dolomitization and burial dissolution played constructive roles, resulting in a porosity increase to 20%. Given that a few doloarenites have grained-texture (Figure 2(d) and (e)), the estimated porosity value was calculated by adding the porosity value of the doloarenite from this study to the estimated volume fraction of second-generation cementation from the thin sections.

(f) In late late-diagenetic period, diagenetic conditions changed dramatically owing to Cretaceous tectonic movement (Liu and Sun, 2009). The tectonic uplift produced fractures and released pressure. The diagenetic environment became an open system with active geological fluids. Destructive diagenesis, including recrystallization, mineral filling, cementation, de-dolomitization (Figure 2(k)), de-gypsification (Figure 2(j)), compaction, pressolution, and replacement decreased porosity greatly to approximately 3%. The burial dolomitization and burial dissolution may have improved pore structure and produced pores, resulting in the formation of relatively high-quality reservoirs with porosity ranging between 5% and 8%, which approximates intercrystalline pores of the planar-euhedral dolomites. Some studies have proposed that hydrothermal dolomitization plays a significant role in reservoir formation (Huang, 2011; Wang et al., 2008, 2009); however, limited hydrothermal activity produced only some hydrothermal mineral filling of pores. It did not reach the degree of hydrothermal dolostone formation given in the petrographic criterion (Davies and Smith, 2006).

Although the reservoirs have experienced severe diagenetic modification, relict textures of grains can still be vaguely discerned microscopically, which indicates that high-quality reservoirs are developed in the facies associations related to peritidal shoals, as predicted above. The doloarenites probably evolved into the best reservoirs because residual intergranular pores persisted through the diagenetic process. This might provide the permeability pathways for geological fluids during the diagenetic process (Woody et al., 1996; Zhao and Jones, 2012), creating favourable conditions for constructive dolomitization and dissolution that resulted in the formations of planar-euhedral dolomites and solution pores. Consequently, some doloarenites were transformed into crystalline dolomites with more ideal crystal shapes. The measurement of fluid inclusion homogenization temperatures in dolomites with relict fabric-retentive textures and good crystal shapes indicated temperatures between 90.0°C and 125.9°C. According to the mean geothermal gradient of the basin (2.93°C/100 m; Ren et al., 2007), the diagenetic temperatures reflected by the fluid inclusions is roughly consistent with normal burial temperatures. The homogenization temperatures of the inclusions are also nearly equal to the maximum simulation temperatures reconstructed from modelling the burial thermal evolution history (Guo et al., 2014). In other words, the homogenization temperatures of the inclusions in crystalline dolomite record the normal burial precipitation temperatures of dolomites, showing that burial dolomitization was the terminal mechanism for most of the dolomite formations. X-ray diffraction analysis of dolomite samples shows a high degree of ordering, with a mean value of 0.788 (Table 2), indicating that the dolomites had enough time to form near-ideal, well-ordered crystal structures, which is further evidence of burial dolomitization.
The $^{13}$C values of the dolomites, ranging from $-3.43$ to $0.5$ with a mean of $-1.64$, are typical of Ordovician marine facies (around $0–2.2$; Shields, 2003; Figure 9(a)). This suggests that carbon in the minerals was sourced mainly from carbonate strata deposited under contemporaneous marine conditions. Information about the fluid from which the dolomite precipitated can be extracted from mapping cross-plots of the fluid inclusion homogenization temperature versus the O isotope signature of a fluid that is in isotopic equilibrium with the dolomite (Figure 9). A comparison between the $^{18}$O values of the contemporaneous seawater ($-8.5$ to $-5.5$; Veizer et al., 1999) and corresponding samples implies that the dolomites in sub-members M5$^6$ and M5$^5$ were formed from $^{18}$O-rich solutions (Figure 9(b)). Owing to kinetic isotope effects in evaporation, the evaporative phases of water accumulate light oxygen and thus have low $^{18}$O, whereas the residual phases gather heavy oxygen and have higher $^{18}$O. Therefore, $^{18}$O is relatively high in associated seawater, especially seawater that is concentrated by evaporation and high-salinity formation water. As indicated above, the contemporaneous abnormal seawater was the source of the $^{18}$O-rich geo-fluid. The dolomites of the Majiagou Formation interbed with evaporate layers, and these facies associations were formed in restricted cratonic epeiric seas (Figure 6). The combination of solar-driven evaporation and the classic mechanism of centripetal concentration resulted in a stratified high-salinity centre (Chen et al., 2018). The dense high-salinity brines would have been trapped in pore waters and voids within the precipitating carbonates and evaporites. A 1 change in the $^{18}$O value of seawater is associated with a 2.9 change in its salinity (Craig, 1966; Zhang and Le, 1981). This suggests that solutions from which the dolomite precipitated were concentrated seawater that underwent evaporation during deposition; thus, their salinity was at least 11.6 higher than the Dapingian (Middle Ordovician) normal seawater (around 40–45, Hay et al., 2006). According to Gregg and Sibley (1984) and Sibley and Gregg (1987), the shape of dolomite crystals is controlled by growth kinetics, which are affected predominantly by temperature and salinity. In this case, the $^{18}$O rich geo-fluid was likely to be abnormal seawater hosted in pores of contemporaneous rocks in the intracratonic depression.

In conclusion, about 3% of the porosity in the present dolomite reservoirs can be attributed to residual intergranular pores and intercrystalline pores. During the diagenetic evolution process, intense recrystallization welded some dolomites into large patches (Figure 2 (i)). Some doloarenites experienced two generations of cementation (Figure 2(a)), compaction and pressolution, that formed a tight nodular structure (Figure 2(l)), with minerals such
as dolomite, calcite, authigenic quartz, and pyrite filling some intergranular pores, solution pores, and solution fractures (Figure 2(c)). These destructive diagenesis processes partly reduced porosity and weakened the connectivity of pores, resulting in low porosity and a low permeability gas-bearing reservoir. As discussed, burial dolomitization and burial dissolution were the two most important factors in improving the quality of the dolomite reservoirs. The former mostly improved the pore structure, while burial dissolution raised the volume of the porosity. The crystalline dolomites with rhomb shaped crystals and higher porosity remain relict grains, which indicates that the dolomitization was facies-selective and most likely to occur in peritidal shoal facies associations. This provides a referential solution for predicting potential dolomitic reservoirs.

Potential for exploration in intracratonic basins

Following the discovery of the Puguang Gas Field, recent (<10 years) exploration focused on carbonate platform marginal facies for seeking reef- or shoal-reservoirs in China. This has deeply influenced gas-exploration decisions in the Ordos Basin. Before 2010, Oil corporations were focused on finding new types of gas carbonate reservoirs (i.e., besides the karst reservoir discovered in 1989). Nearly all of the proposals have targeted the westernmost and southernmost Ordos Basin, aiming at platform marginal facies associations. This study revealed that deep carbonate rocks in the intracratonic Ordos Basin should also be potential targets of oil and gas exploration. Our conceptual models provide a new interpretation for Majiagou reservoirs and guide us to change the exploration strategy from platform marginal to intracratonic basin. Our findings are supported by the new discovery of the gas play in the intracratonic Ordos Basin. Our results support the hypothesis that the dolomites and evaporates formed from a restricted platform (Hou et al., 2003), but were not deposited on an opening shallow sea (Li et al., 2012; Yao et al., 2008) or multi-trough-cutting platform (Fu et al., 2017). Even though there was no Ordovician rimmed platforms on the shelf of the North China Plate, geomorphologic bumps would block seawater energy allow for the formation of a plate-scale epeiric sea platform (Chen, 2010). Our proposed depositional and diagenetic models deviate from other popular models, which overemphasize marginal facies associations and only consider the detection of these associations around rifts or troughs hidden in cratonic basins. The epeiric platform model suggests that the exploration of intracratonic tidal flat sequences should compare favourably with rimmed platform sequences. The discoveries of Sichuan Basin has also implied that deep carbonates of such intracratonic basin in China should be considered as favourable targets for natural gas exploration (Shi et al., 2017, 2018; Zhou et al., 2015). Therefore, this study provides additional support for the exploration of deep carbonate reservoirs in intracratonic basins. Our results give new insights into intracratonic tidal flat sequences, with competitive potential-resource comparing to the reservoir of marginal facies associations, as targets for giant oil and gas fields.

Conclusions

a. Gas reservoirs of sub-members M₅⁴ and M₅⁶ are mainly composed of crystalline dolomites and doloarenites, with intercrystalline, residual intergranular, and dissolution pores. The reservoirs have peak porosities between 2% and 5%, and permeability of
0.01–5 mD, classing them as low porosity, low permeability reservoirs with strong heterogeneity.

b. The depositional environment of this new type of reservoir was a tidal flat on a semi-restricted platform. A distinctive feature of the platform was the peritidal shoal facies association, which is distributed along the inner side of the Central Paleo-uplift. Doloarenites with phantom grained-texture are formed in the peritidal shoal initially and are almost unrecognizable.

c. Destructive diagenesis (e.g., recrystallization, cementation, compaction, pressolution, and mineral filling) led to densification of the dolomites. Burial dolomitization and burial dissolution of selected sedimentary facies likely occurred in the peritidal shoal facies association, and were the key factors in improving the physical properties of the dolomitic gas reservoirs.

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