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RESEARCH ARTICLE

Study on the law of elastic parameters of carbonate rock under differential burial history and diagenesis

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Abstract There are some high-quality reservoirs of internal dolomite within the Ordovician Majiagou Formation in the Ordos Basin, located in western China. However, influenced by sedimentary environments and differential diagenetic processes, these high-quality dolomite reservoirs exhibit thin sedimentary thickness and relatively small differences in elastic parameters compared to the surrounding rocks. Identifying these reservoirs using seismic data presents a significant challenge. In the study area, systematic sampling was conducted, and the physical and elastic properties of dolomite, limestone, and anhydrite were tested in the laboratory. Through various analyses, including physical property tests, thin-section observations, and CT scans, researchers discovered that the carbonate rocks in the study area underwent complex diagenetic evolution. The primary constructive diagenetic processes include dolomitization and dissolution; while the main destructive diagenetic processes involve compaction and cementation. Dolomitization leads to abundant intercrystalline pores, increasing rock porosity. The pore aspect ratio is relatively large, with predominantly near-circular pores. Additionally, because the longitudinal wave velocity of dolomite minerals exceeds that of calcite, dolomitization enhances the rock’s elastic parameters. Dissolution primarily alters pore shape, increasing rock porosity while reducing the aspect ratio of pores (mainly flattened pores). Consequently, this decreases the rock’s elastic parameters. Different diagenetic processes significantly impact the elastic parameters of the rocks. By analyzing the differences in elastic parameters before and after various diagenetic processes, researchers can clearly define the elastic parameter characteristics of high-quality dolomite reservoirs, providing a foundation for reservoir prediction in the study area.

Keywords Ordos Basin, carbonate rocks, diagenesis, dolomitization, dissolution, pore structure

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1 Introduction

Dolomite reservoirs have always been a key focus in the exploration and research of carbonate oil and gas, especially with the rapid development of deep oil and gas exploration. More and more deep dolomite oil and gas reservoirs are being encountered during drilling (Jin, 2005; Ma et al., 2020). The formation mechanism of dolomite reservoirs is still unclear, and there are large errors in the method of predicting high-quality reservoirs using seismic data, which makes the exploration of deep dolomite oil and gas still have many deficiencies (Bao et al., 2017; Lei et al., 2020; Yang et al., 2020; Zhou et al., 2020; Fu et al., 2021).

The Late Paleozoic Ordovician Majiagou Formation in the Ordos Basin is a set of strata widely developed in marine carbonate rock in China. The high-quality reservoir of karst weathering crust is formed in the upper combination of Majiagou Formation, which is the result of the overall uplift of the stratum in Caledonian movement and the transformation by weathering, leaching and denudation. The dominant pore type of this reservoir is dissolution pores. Extensive research has been conducted on the paleogeography, lithofacies, and diagenesis of marine carbonate rocks during the period of karst weathering shell formation, resulting in significant insights (Li et al., 2012; Zhang et al., 2017; Fu et al., 2019; Luo et al., 2020; Zhou et al., 2020). In recent years, with the deep exploration, thin layers of dolomite between limestone or gypsum rocks have been discovered inside the 4th Member of Majiagou Formation, which is far away from the weathered crust. They also have high porosity and well hydrocarbon, making them an important field for the next step of oil and gas exploration in the Majiagou Formation. However, it is difficult to predict the high-quality dolomite reservoir, due to the dolomite reservoir which developed under the layer of gypsum, have the characteristic of thinner, stronger heterogeneity and smaller impedance difference from surrounding rocks (Ding et al., 2021; Wei et al., 2021; Wu et al., 2021; He et al., 2022). Although the technology predicting the distribution of deep dolomite has made significant progress in recent years, the strong heterogeneity determined by the multi-scale and multi type reservoir space of deep high-quality dolomite reservoirs has led to multiple solutions in reservoir prediction results, and the prediction accuracy of high-quality dolomite reservoirs is not high (Weger et al., 2009; Pan et al., 2020; He et al., 2021). To accurately predicted deep dolomite reservoirs use the seismic data, many scholars have carried out a lot of research on Carbonate rock petrophysical experiments, modeling and the impact of pore structure on Carbonate rock elastic parameters using the equivalent medium theory (Mori and Tanaka, 1973; Kuster and Toksöz, 1974; Berryman, 1980; Zimmerman, 1984; Norris, 1985; Berryman et al., 2002; Wang et al., 2023a). According to the analysis of these studies, the mineral composition, porosity and pore morphology of rocks will be changed by the complex diagenetic evolution process of Carbonate rock reservoir. Therefore, in order to accurately predict the high-quality deep Carbonate rock reservoir, it is necessary to establish a petrophysical model with geological genesis guidance and quantitatively predict the impact of different Diagenesis on the rock characteristics. Up to now, numerical simulation and dissolution experiments are mainly used to qualitatively or semiquantitatively reflect the relationship between different Diagenesis and porosity and pore structure, and then study the evolution law of porosity and pore structure in dolomite reservoirs at different diagenetic stages (Bakke and Øren, 1997; Tarafdar and Roy, 1998; Sadhukhan et al., 2007; Wang et al., 2007; Remeysen and Swennen, 2008; Sok et al., 2010; Xie et al., 2010). Although these research ideas provide guidance for the prediction of dolomite reservoirs in the Ordos Basin, they are still far from sufficient for accurately predicting areas where high-quality dolomite reservoirs develop. Consequently, this paper, based on basic geological experiments and petrophysical experiments, analyzes the impact of different Diagenesis on elastic parameters, and establishes a quantitative interpretation chart of pore structure of different lithology in the study area.

There are the restricted platform and platform margin in the 4th Member of Majiagou Formation, Ordos Basin. In this paper, we will focus on the middle-east of Ordos Basin, where only the restricted platform is present. There are some calcareous-dolomitic flat and dolomitic calcific flat in the restricted platform, and the intra-platform mounds and shoals are typically developed in the uplifted zone (Fig. 1). Sedimentary environment primarily influences the thickness of dolomite reservoirs. The lithological distribution characteristics within the basin are influenced by paleogeographic conditions. Limestone is mainly found in the eastern depression of the basin, while locally, dolomite is relatively well-developed in high paleotopographic areas. Moving from west to east, the content of dolomite gradually decreases, and it transitions into limestone or gypsum. Additionally, in the low uplifted areas within the plateau, where water energy is higher, favorable conditions exist for the development of carbonate rocks in shoal facies. Here, dolomite content is higher, resulting in relatively thicker dolomite layers (Guo et al., 2023). Due to the nearly north–south distribution of ancient uplifts, the distribution of dolomite also exhibits a north–south banded pattern.

2 Methodology

2.1 The porosity and pore structure characteristics of the 4th Member of Majiagou Formation

The physical properties of sediment in the 4th Member of Majiagou formation are relatively poor. Based on the results of physical property tests on actual samples from the study area, the porosity varies within the range of 0.336% to 6.732%. Most of the porosity samples between 0.3% and 2%, and there is a noticeable increasing trend in porosity with an increase in dolomite content. The permeability ranges from 0.0002 mD to 1.46 mD, with the majority of permeability values below 0.1 mD (Fig. 2). The correlation between porosity and permeability is weak, especially in samples with porosity less than 2%.

During diagenesis, the 4th Member of Majiagou Formation carbonate rocks experienced various processes, including compaction, dissolution, cementation, replacement, and filling. Drilling core and thin section observations reveal that the predominant reservoir spaces in the 4th Member of Majiagou Formation carbonate rocks are intercrystalline pores, intercrystalline dissolution pores, and fractures. Intercrystalline pores primarily occur in ancient uplifts or paleohighs and are formed later through dolomitization. They often exhibit polyhedral or triangular geometries, with smooth and straight pore walls. The pore sizes typically range from 10 μm to 50 μm, resulting in relatively large aspect ratios (Figs. 3(a)–3(d), indicated by green arrows). Intercrystalline dissolution pores develop on the basis of intercrystalline pores, enlarging through selective dissolution of minerals such as carbonate. These pores have irregular shapes, with sizes ranging from 30 to 200 μm and smaller aspect ratios (Figs. 3(a) and 3(b), indicated by pink arrows). Fractures mainly include structural fractures and dissolution fractures, with near-horizontal and oblique intersections.

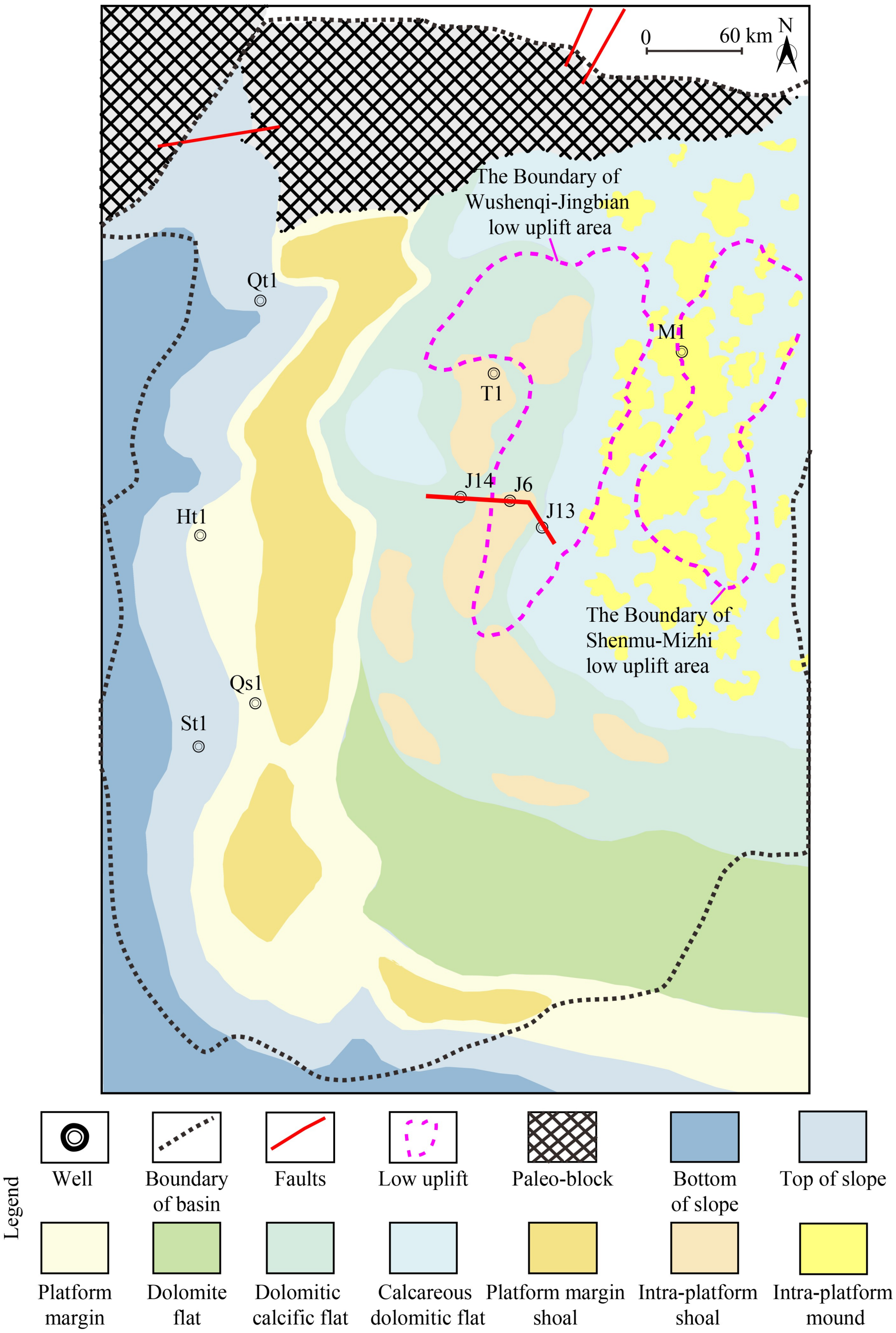

Fig. 1 The lithofacies paleogeographic map of the 4th Member of Majiagou Formation, in the Ordos Basin (revised according to He et al., 2022 and Wang et al., 2023a).

The aspect ratios of these fractures are quite small (Figs. 3(e) and 3(f), indicated by red arrows).

2.2 The diagenetic evolution sequence of the 4th Member of Majiagou Formation in the Ordos Basin

The dolomite of the 4th Member of Majiagou Formation undergone dynamic evolution of penecontemporaneous dolomitization and burial dolomitization. During penecontemporaneous period, water is relatively shallow beside the land, the sea water concentrated because of hot weather and the concentrated salty water filtrate and circumfluence downwards and metasomatism the early sediments. Early penecontemporaneous dolomitization strengthen the capacity of anti-compaction, it is conductive for the reservation of penecontemporaneous pores. In the late burial diagenesis environment, the overlay clay mineral of upper Paleozoic dewatered and generated Mg^{2+} to encourage the early formed dolomite to re-crystallized to be fine crystalline dolomite or residual grained structural dolomite, further improved the reserve propriety of the dolomite reservoir or expanded

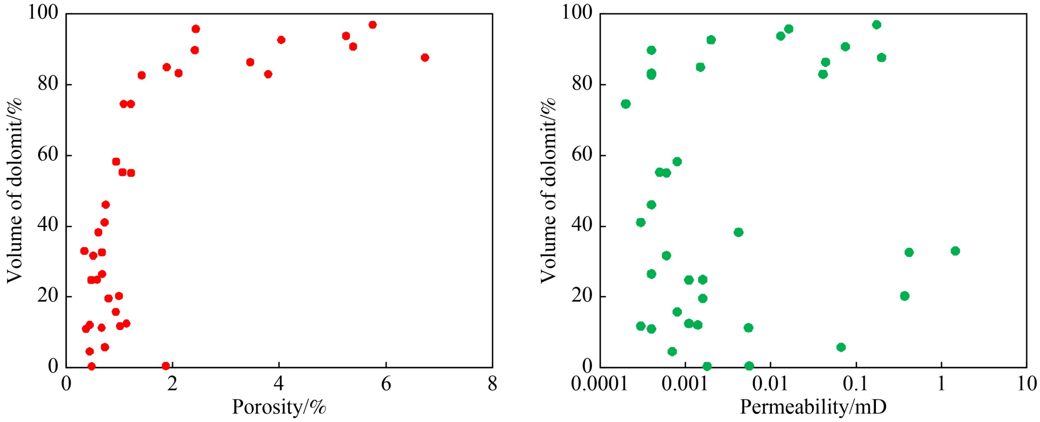

Fig. 2 The crossplot of physical properties and dolomite content of rock samples from the 4th Member of Majiagou Formation in Ordos Basin.

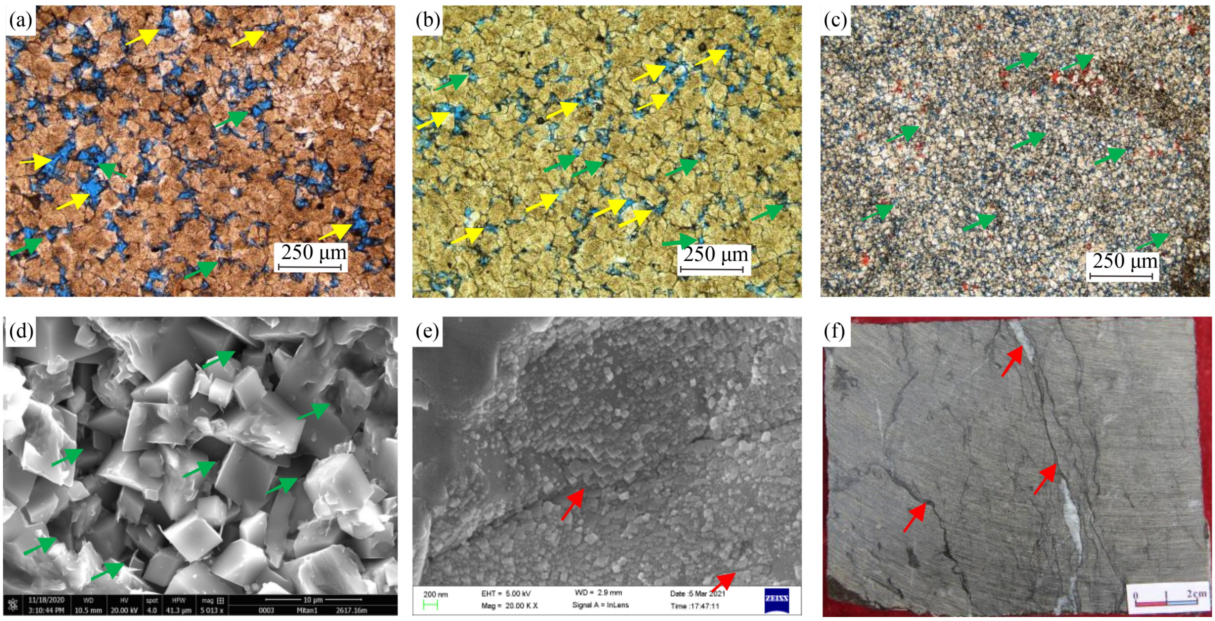

Fig. 3 The typical character of lithology pore structure in the 4th Member of Majiagou Formation. In those pictures, the yellow arrows mean dissolution pores, the green arrows mean matrix pores, and the red arrows means cracks. (a) Well S6, 3688.14 m, fine crystalline dolomite, thin-section (the blue is pores), intercrystalline dissolved and intercrystalline pores; (b) Well S6, fine crystalline dolomite, thin-section (the blue is pores), intercrystalline dissolved and intercrystalline pores; (c) Well T1, 3708.42 m, powdery crystalline dolomite, thin-section (the blue is pores), reddish calcite filled in grains, intercrystalline pores; (d) Well M1, fine-powdery crystalline dolomite, scanning electron microscope, intercrystalline pores; (e) Well T1, powdery crystalline dolomite, scanning electron microscope, micro-fracture; (f) Well M1, the core of gray argillaceous limestone, Diagonal or horizontal cracks be filled by calcite.

the distribution area of the dolomite reservoir. Meanwhile, it continuously metasomatized early non-dolomitized limestone, but this type of dolomitization rock cannot form the valid reservoir, such as dolomitic limestone, refer to Fig. 4.

2.3 The characteristics of elastic wave velocity with effective pressure

The elastic properties of rocks are primarily determined through ultrasonic measurements of P-wave and S-wave velocities on rock samples. For this experiment, we selected samples at depths ranging from 2690 m to 3880 m, subject to confining pressures between 60 MPa and 110 MPa. Locally, there is unusually high pore pressure, and the coefficient of pore pressure can reach 1.5. To investigate these properties, we employed an SCMS-SD high-temperature and high-pressure rock core acoustic-electric measurement instrument to measure P-wave and S-wave velocities in the ultrasonic frequency range. We conducted velocity measurements under effective pressure of 0, 5, 10, 20, 30, and 40 MPa, both in dry and water-saturated conditions. In addition to analyzing the characteristics of elastic wave velocity with effective

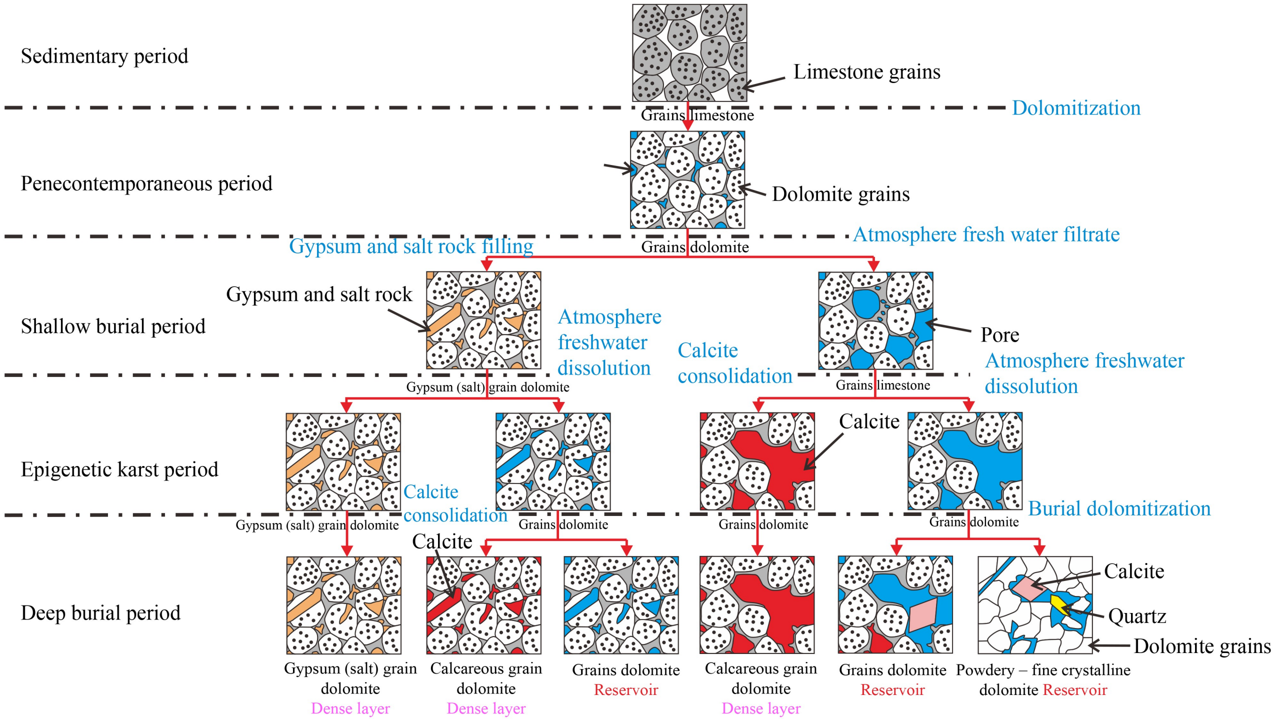

Fig. 4 Evolution and development process of dolomite reservoir in Majiagou Formation of Ordos Basin (revised according to Wu et al., 2021).

pressure, subsequent analysis focused on the elastic parameters of the samples at 20 MPa, corresponding to reservoir conditions.

Based on the geological background of the study area, we conducted elastic characterization tests on four types of samples: dissolved pore type dolomite, intercrystalline pore type dolomite, cracked-pore type limestone, and dense limestone. The porosity of these four sample types is as follows: 6.73%, 3.5%, 0.75%, and 0.51%, respectively. From the Fig. 5, it is evident that the velocity response to effective pressure varies for different pore structures. Specifically, cracked samples and dense samples exhibit a significant increase in velocity with increasing effective pressure. They demonstrate high-pressure sensitivity, characterized by rapid velocity increase in the low-pressure range and a gradual decrease in the rate of increase at higher pressures. Intercrystalline pore type dolomite and dissolved pore type dolomite samples show slow velocity increase with increasing pressure, indicating low-pressure sensitivity. This behavior is attributed to the fact that soft pores with smaller aspect ratios (such as cracks) are more sensitive to pressure changes and tend to close as pressure increases. In contrast, dissolved pores and intercrystalline pores, which have larger aspect ratios, exhibit greater resistance to closure under pressure.

When comparing water-saturated samples with gas-saturated samples, the P-wave velocities increase. However, the velocity trends differ among specific pore types. Samples with smaller aspect ratios experience a larger increase in velocity compared to those with larger aspect ratios.

Despite the trend of increasing S-wave velocities with effective pressure, the variation patterns are relatively similar among different sample types. Pore structure has a minor impact on S-wave velocities in the study area due to the generally small porosity of the rocks.

2.4 The method to calculate pore structure based on multi-pore DEM model

The differential effective medium (DEM) theory models two-phase composites by incrementally adding inclusions of one phase (phase 2) to the matrix phase. In this model, all pores are considered equivalent, possessing the identical pore structure, which has led to its widespread use in isotropic reservoirs or the sandstone. Through the analysis of the results of rock physics experiments, it is known that the pore structure has a significant impact on the elastic parameters in the study area. Therefore, in order to effectively predict the distribution of high-quality reservoirs in the study area, it is necessary to study the quantitative method for calculating pore structure. The DEM model has been extended from single-pore media to multi-pore media. The initial differential equation for calculating the dry skeletal modulus of porous rocks can be expressed as follows:

$$(1-\phi)\frac{\mathrm{d}K^*(\phi)}{\mathrm{d}\phi} = \sum_{i=1}^{N} v_i\left[K_i - K^*(\phi)\right]P^{*i}, \tag{1}$$

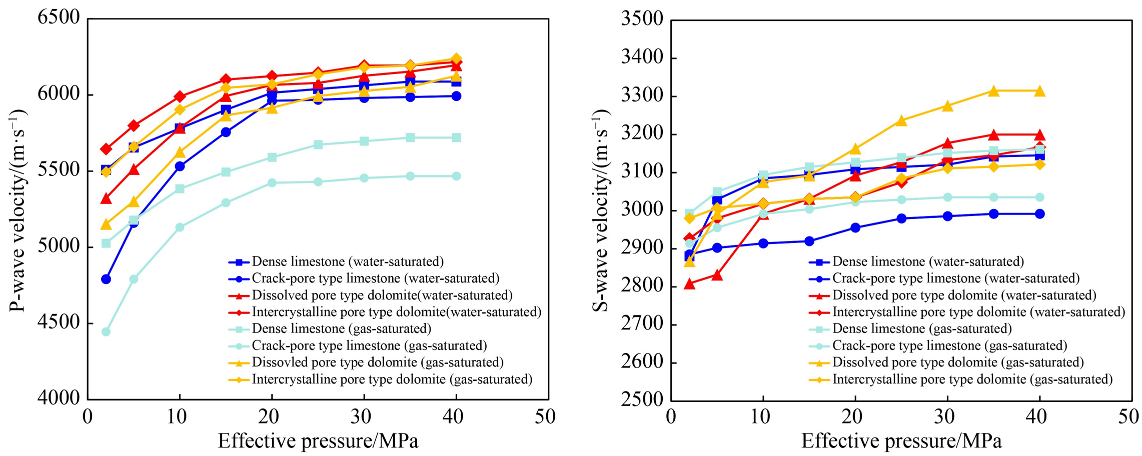

Fig. 5 Velocity variation with effective pressure and microscopic characteristics of typical samples in the 4th Member of Majiagou Formation. (a) The P-wave velocity and the effective pressure; (b) The S-wave velocity and the effective pressure.

$$(1-\phi)\frac{dG^*(\phi)}{d\phi} = \sum_{i=1}^{N} v_i [G_i - G^*(\phi)] Q^{*i}, \qquad (2)$$

where ϕ is the porosity and $d\phi$ is the small increment in porosity; $K^*(\phi)$ and $G^*(\phi)$ representing the effective bulk modulus and shear modulus of complex rocks, respectively. v_i representing the volume of ith type of pore in the total porosity. P^{*i} and Q^{*i} representing the pore geometry factor of the $K^*(\phi)$ and $G^*(\phi)$, respectively, they are controlled by the aspect ratio of pores. N is the number of pore types, and when N = 1, the above equation is equivalent to the classical DEM model of dry rocks; when N = 3, the above equation becomes the triple pore model.

3 Results and discussions

3.1 The main controlling factors for the formation of high-quality dolomite reservoirs

According to the pore characteristics and pore structures of different carbonate rocks in the 4th Member of Majiagou Formation of the central-eastern Ordos Basin, it can be inferred that the primary reservoir lithology is dolomite, with the content of dolomite exceeding 80%. The pore structure of high-quality reservoirs is mainly composed of intercrystalline dissolution pores and intercrystalline pores. The dolomite, which has been transformed by dolomitization and dissolution, is the rock with the best physical properties in this region, located on the intra-platform mounds and shoals.

3.1.1 The intra-platform mounds and shoals is the material basis for dolomite reservoirs

The formers studies indicate that the maximum initial porosity of the grained beach sediments can reach 40%−50%, this build up well physical basis for the reservoir (Ma et al., 2005; Ding et al., 2017). The sedimentary period of the 4th Member of Majiagou Formation in Ordos Basin was characterized by relative transgression, during which the basinal seawater was connected to the Huabei Sea. Because of this, the sea water circulated freely and the hydraulic power was higher. As a result, the central uplift, Wushenqi-Jingbian low uplift and Mizhi low uplift can deposit some rocks of grained beach facies. After penecontemporaneous dissolution and dolomitization, those rocks can develop better grained beach facies of dolomite reservoir in the study area. From the lithology paleogeography map of the 4th Member of Majiagou Formation, we can observe two distribution zone of granular beaches along the uplift in the middle and east of basin.

3.1.2 Dolomitization is an important factor for the effective preservation of reservoir space

Dolomitization is a process in which Mg^{2+} in the fluid that contain richer Mg^{2+} will replace Ca^{2+} in Carbonate rocks. Due to the exchange of cations, the internal structure of the original rock is changed, resulting in shrinkage of crystal volume and enhanced compressive strength. Exploration shows that the reservoir space types of the 4th Member of Majiagou Formation are mainly intercrystalline pores and intercrystalline pores, which mainly occur in dolomite. From Fig. 6, it can be observed that dolomite has higher porosity and permeability than other lithologies.

3.1.3 Dissolution is the key factor in the formation of high-quality reservoirs

At the late of Caledonia, due to Tectonic uplift, the Ordos Basin experienced a weathering exposure period of more than 100 million years. For this reason, the atmospheric fresh water would further dissolve and expand the pore space of rocks in the fourth member of Majiagou

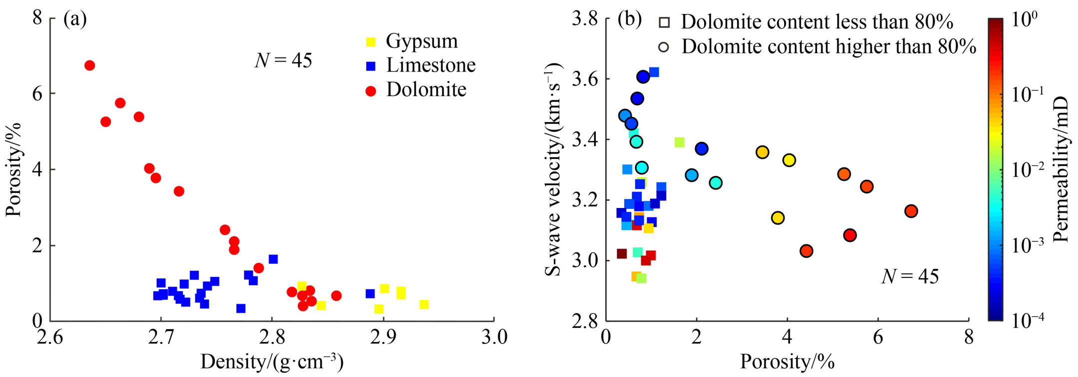

Fig. 6 The cross plot of samples in the study area. (a) The cross plot of density and porosity; (b) The porosity and S-wave velocity.

Formation in the uplift area of the basin, and the rocks that had experienced the dissolution and transformation during this period will contain dissolved pore type and dissolved fracture type pores.

Dissolution not only increases pore space, but also changes the shape of pores, forming a large number of flat pores, which are more easily interconnected, and thereby increase the permeability of rocks, leading to the formation of high-quality reservoirs.

In conclusion, the influence of the main Diagenesis in the study area on the reservoir can be classified into two categories, in which dolomitization, dissolution and fracturing are constructive Diagenesis, and compaction, cementation and filling are destructive Diagenesis. Dolomitization can alter the mineral composition of rocks, resulting in changes in the matrix modulus of rocks and forming the matrix pores, like the intercrystalline pores and intercrystalline pores. Dissolution can change the shape of pores, forming flat pores that are similar to the reference pores defined in the Xu-Payne model. Therefore, quantitatively identifying the volume proportion of different pore types can effectively predict high-quality reservoirs in the study area.

3.2 Relationship between P-wave impedance and Poisson's ratio

In quantitative seismic interpretation, the P-wave impedance and Poisson's ratio play indicative roles (Wang et al., 2023b). The relationship between P-wave impedance and Poisson's ratio in the study area is influenced by pore structure, pore fluids, and mineral composition (Fig. 7). Under dry conditions, the P-wave impedance and Poisson's ratio of gypsum are significantly higher than those of limestone and dolomite due to mineral composition effects. For the same rock type, as porosity increases, both P-wave impedance and Poisson's ratio decrease. Among different pore types, crack-type pores exhibit a more rapid decrease than dissolution-type samples, while intercrystalline pores show the least variation.

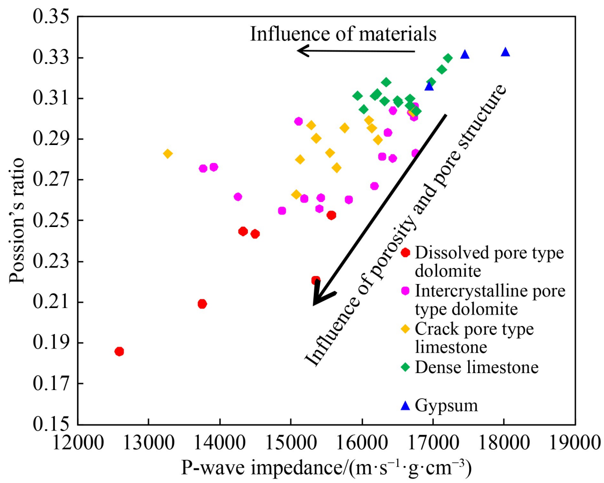

Fig. 7 Relationship between P-wave impedance and Poisson's ratio of the 4th Member of Majiagou Formation samples.

3.3 Quantitative interpretation template and application of rock physics for the 4th Member of Majiagou Formation carbonate rocks

Due to the difference in diagenesis of rocks in different sedimentary environments, the mineral composition and pore type of rocks in the study area will be different. Therefore, we will establish pore structure identification templates for different lithology, and introduce the pore aspect ratio to quantitatively characterize the differences in pore structure. In rock physics research, we consider pores as an ellipsoid, and the aspect ratio of pores is the ratio of the short axis to the long axis of the ellipsoid.

First, the DEM model would be used to calculate the pore aspect ratio of different type of pores, and this model contain Eqs. (3) and (4). By input the parameters of rock matrix modulus and porosity into the Hashin-Shtrikman upper boun, Hashin-Shtrikman lower bound, and Wyllie time average equation, the P-wave velocity of samples would be calculated. Adjust the pore aspect ratio so that the calculated P-wave velocity matches the actual measured P-wave velocity. When these two velocities are equal, the aspect ratio used is equivalent to the pore aspect ratio for a single pore type. The calculation results are shown in Fig. 8.

$$K(\phi+\mathrm{d}\phi)=K(\phi)+\frac{1}{3}\left[K_f-K(\phi)\right]\sum_{i=c,hc}\phi_i T_1\frac{\mathrm{d}\phi_i}{1-\phi_i}, \quad (3)$$

$$\mu(\phi+\mathrm{d}\phi)=\mu(\phi)+\frac{1}{5}\left[\mu_f-\mu(\phi)\right]\sum_{i=c,nc}\phi_i T_2\frac{\mathrm{d}\phi_i}{1-\phi_i}. \quad (4)$$

With initial conditions $K(0) = K_m$ and $\mu(0) = \mu_m$, where K_m and μ_m are matrix bulk and shear modulus respectively. K_f and μ_f are the bulk and shear modulus of inclusion phase, respectively. ϕ is the porosity and $\mathrm{d}\phi$ is the small increment in porosity. T_1 and T_2 are the geometrical factors depending on aspect ratio of the elliptical pores.

To estimating the effective aspect ratio of matrix pores, dissolution porosity and microporosity or cracks, one needs an extra input along with the bulk porosity available. This can be any elastic modulus or the P-wave or S- wave velocities. P-wave velocities are typically available in the form of sonic log or laboratory measured data for water saturated core samples. Using the results of aspect ratio, we introduce the DEM model of Porous medium to establish a chart for quantitative interpretation of pore shape, as shown in Fig. 9. The Fig. 9(a) is the quantitative interpretation chart of the pore structure for dolomite, and Fig. 9(b) is the chart for limestone. In the figure, the horizontal axis represents porosity, the vertical axis represents P-wave velocity, and the percentage represents the volume fraction of dissolution pores in the rock. From the Fig. 9, it can be observed that under the

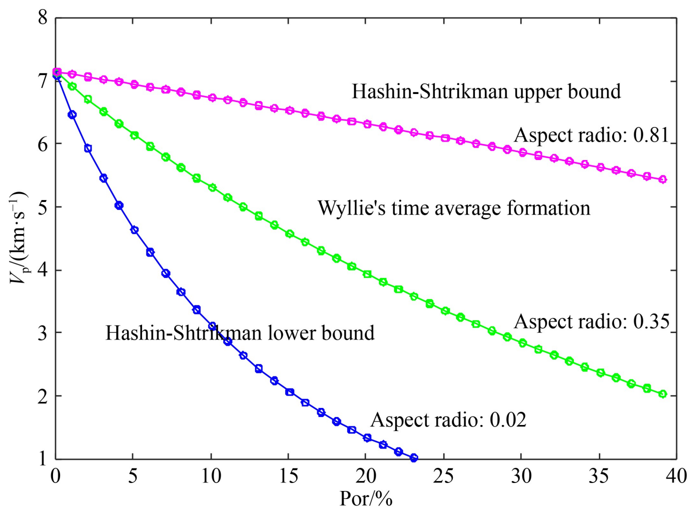

Fig. 8 The result for DEM model calculated the aspect ratio if only one type pore in the rocks. The pink line is Hashin-Shtrikman upper bound, which can equal the aspect radio is 0.81; the green line is Wyllie time-average, which can equal the aspect radio is 0.35; and the blue line is the Hashin-Shtrikman lower bound, which can equal the aspect radio is 0.02.

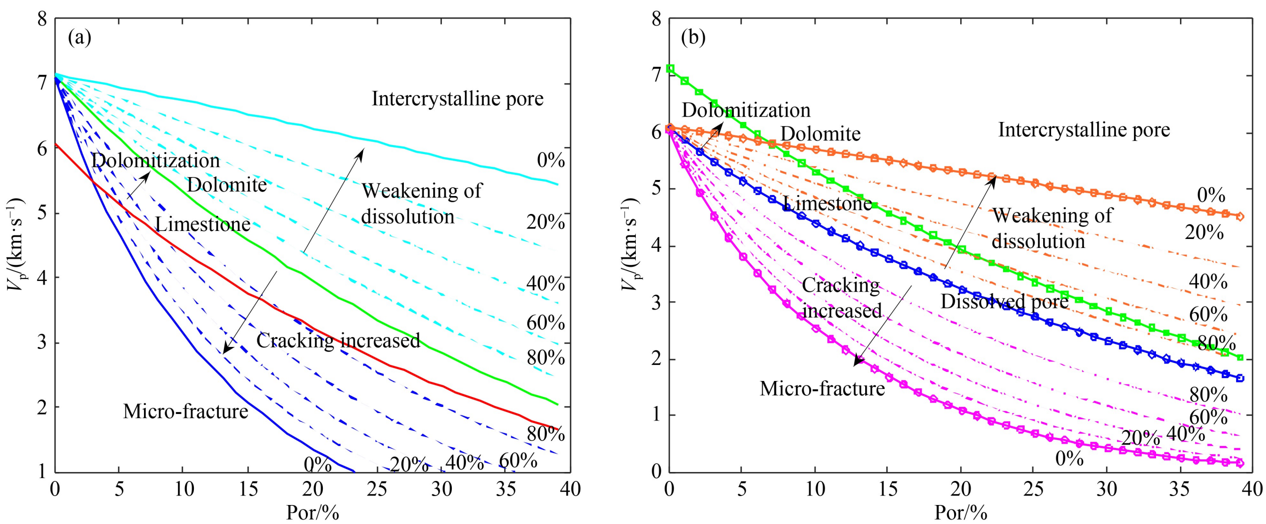

Fig. 9 The chart be used in quantitative interpretation of pore shape in the 4th Member of Majiagou Formation Ordos Basin. (a) Can be used for dolomite; (b) Can be used for limestone.

same porosity condition, when the dissolution is weak, the more the volume fraction of matrix pores, the higher the P-wave velocity of the rock. The stronger the fracturing effect on the rock, the higher the volume fraction of the crack, and the smaller the P-wave velocity of the rock. With the increase of rock dolomitization, the matrix bulk modulus of the rock will increase, that is, the P-wave velocity of the rock will increase at the same porosity.

To verify the practicality of the chart, core data was applied to the chart for quantitative interpretation, as shown in Fig. 10. In the figure, the color of scattered dots represents the dolomite content of the samples, and we can see that red data points are the dolomite content greater than 75% in the samples. Most of the red dots can be explained using the chart for dolomite. In the samples M1-8, the dolomite content is 80.1%, the porosity measured in laboratory is 5.75%, and the P-wave velocity is 6103 m/s. Using the chart for interpretation the pore shape of dolomite, which is established in this paper, the dissolution pore content of the sample is close to 100%. At the same time, the pore types of this sample are dissolution pore as shown by both the result of CT scanning (Fig. 11(a)) and thin sections (Fig. 11(b)), with an average pore aspect ratio of approximately 0.32. In addition, for the samples M1-3, the dolomite content is 83.7%, the porosity measured in laboratory is 3.79%, and the P-wave velocity is 6828 m/s. Using the chart for interpretation the pore shape of dolomite established in this paper, the dissolution pore content of the sample is 30%, and the matrix pore content of the sample is 70%. At the same time, the pore types of this sample are matrix pores and dissolution pores as shown by both the result of CT scanning (Fig. 12(a)) and thin sections (Fig. 12(b)), with an average pore aspect ratio of approximately 0.78.

This method can also be used to predict the distribution of high-quality reservoirs in the study area, primarily characterized by dissolution-type pores. By utilizing seismic pre-stack inversion results, pore type predictions are conducted. Figure 13 illustrates a continuous well-to-

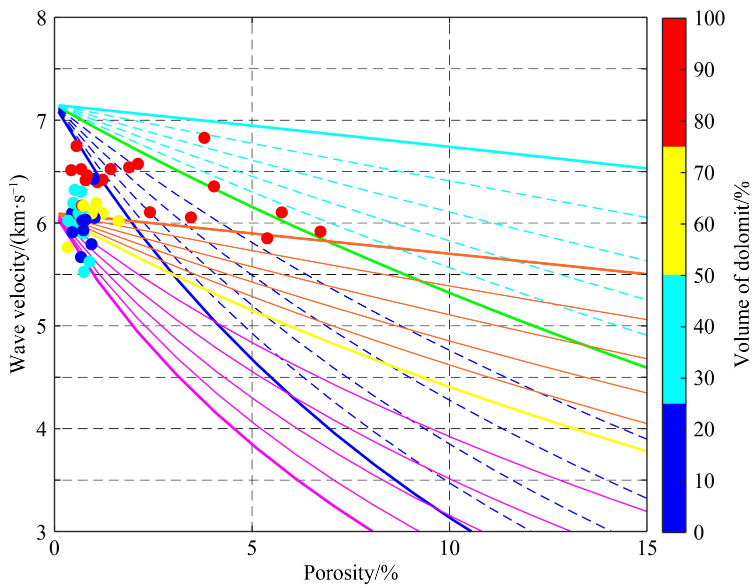

Fig. 10 Application example of quantitative interpretation chart for dolomite pore structure in core sample collected in the 4th Member of Majiagou Formation, Ordos Basin.

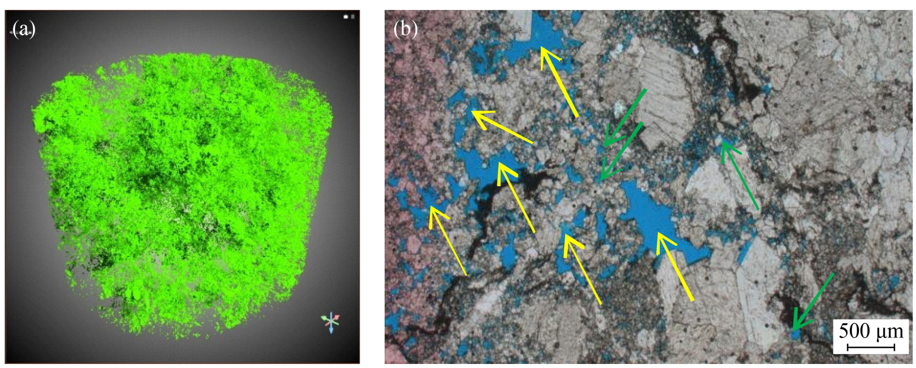

Fig. 11 Characteristics of pore shape of sample M1-8 in 4th Member of Majiagou Formation, Ordos Basin. (a) The CT scanning; (b) Thin section.

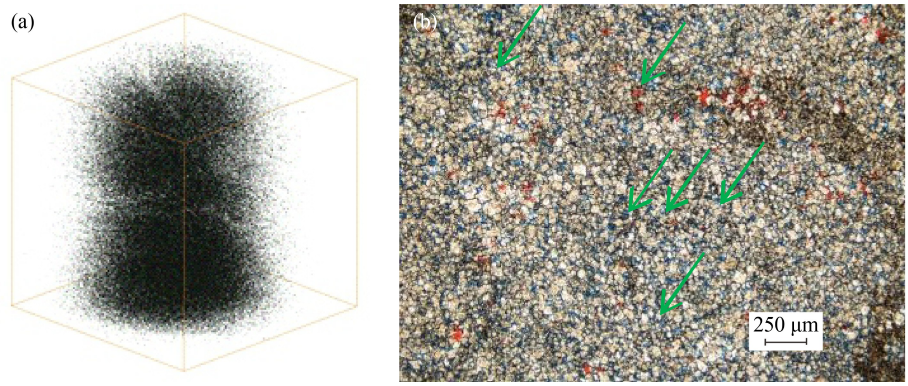

Fig. 12 Characteristics of pore shape of sample M1-3 in 4th Member of Majiagou Formation, Ordos Basin. (a) The CT scanning; (b) Thin section.

well pore structure prediction profile across J14, J6, and J13 wells in the study area, the cross-sectional position is detailed in Fig. 1. Based on actual drilling results, it is observed that the lithology of J6 and J13 wells are primarily composed of dolomite, while J14 well consists mainly of limestone and dolomite. The porosity in the target layer is 6.45%, 5.78%, and 2.84% for J6, J13, and J14 wells, respectively. Among them, J6 well, located at the higher part of the intra-platform, is influenced by both dolomitization and dissolution. The dominant pore types are dissolution pores and intercrystalline pores. J13 well, situated at the lower part of the intra-platform, experiences only dolomitization, resulting in predominantly intercrystalline pores with limited fracture development and poor pore connectivity. J14 well, positioned on the flank of the intra-platform shoal, exhibits weaker dolomitization, leading to underdeveloped porosity. The predicted results effectively reflect the variation patterns in reservoir pore structures across these wells.

4 Conclusions

Through systematic petrophysical testing carbonate rock reservoirs in the 4th Member of Majiagou Formation, Ordos Basin, we have a basic understanding of the characteristics of elastic parameters and physical properties of the carbonate rock reservoirs in the study area. Our analysis lead to the following conclusions.

1) The physical properties of the carbonate rocks in the 4th Member of Majiagou Formation are poor. However, there are some high-quality dolomite reservoirs deposited in the intra-platform mounds and shoals after undergoing reconstruction through constructive diagenesis in the study area. The constructive diagenesis includes dolomitization, dissolution, and fracturing. Dolomitization alters the mineral composition of the rock and increases some matrix pores. Dissolution can change the shape of pores, forming flat pores with a medium aspect ratio, which is a possible characteristic of high-quality dolomite reservoirs.

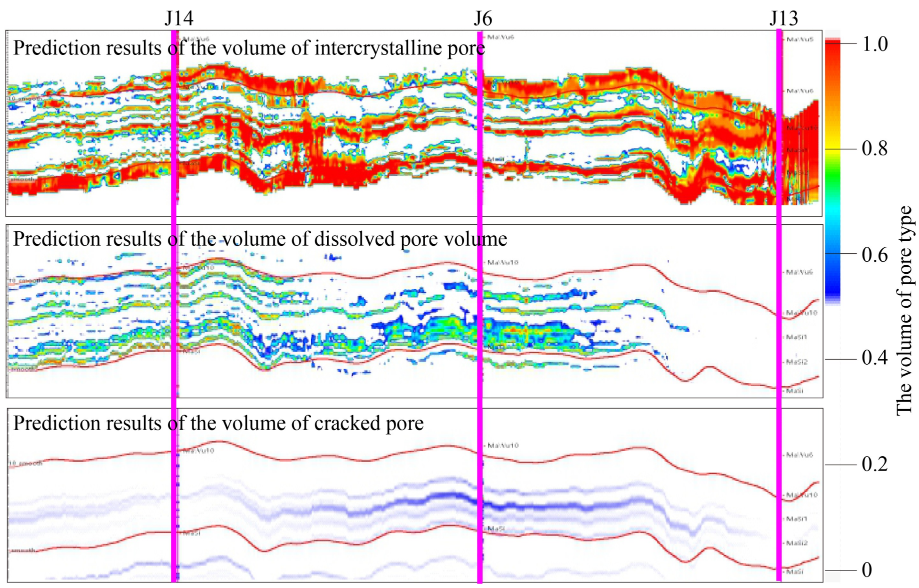

Fig. 13 The predicted results of the distribution of different pore type volumes across wells J14, J6, and J13.

2) By using the DEM (Discrete Element Method) model for porous media, we can quantitatively predict the volume of different pore shapes in the carbonate rock within the study area. Utilizing this model, we have established pore shape interpretation charts specific to various carbonate rock types. These charts were then applied to the actual core data from the study area, resulting in successful application outcomes. Based on the results, we can quantitatively calculate the volume proportion of different pore types in the rocks. This lays the foundation for accurately identifying high-quality reservoirs in the study area, primarily composed of dissolution pores.

Conflict of Interest The authors declare no competing interests.

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