Semiquantitative Characterizations And Controlling Factors of Microscopic Pore Characteristics of The Metamorphic Rock Reservoir In The Central Paleo-Uplift Belt, Songliao Basin

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Abstract

Currently, metamorphic rock is a common target for oil and gas exploration, and reservoirs are the key factors restricting hydrocarbon exploration and development in metamorphic rocks. The deep metamorphic rock gas reservoir in the central paleo-uplift of the northern Songliao Basin has good exploration and development potential. In this study, we use a combination of qualitative descriptions and quantitative analysis to comprehensively analyze the pore characteristics of the reservoir and explore the factors controlling the pore characteristics of the metamorphic rock reservoir in the central paleo-uplift belt of the Songliao Basin. The metamorphic rock reservoir in the central paleo-uplift belt contains three types of lithologies: chlorite schist, mylonite, and mica schist, each with different protoliths and metamorphic histories. The reservoir space can be divided into 4 pore types, and the reservoir space of each lithology is quite different. The results of high-pressure mercury intrusion and nitrogen adsorption indicate that the pore size distributions of the schist and mylonite differ. Compared with the schist, the mylonite has less reservoir space, stronger homogeneity, larger pore size, smaller specific surface area, more natural gas reservoir space and stronger natural gas adsorption capacity. This paper also studies the formation process of the reservoir and divides it into four stages. Finally, this article discusses in detail the factors controlling the microscopic pore characteristics of metamorphic rock reservoirs in the central paleo-uplift belt; the metamorphic rock protolith is the most important controlling factor.

Introduction

Currently, metamorphic rock is a common target for oil and gas exploration, and reservoir properties are the key factors restricting hydrocarbon exploration and development in metamorphic rocks^{1,2}. It is now generally believed that the most important reservoir space in metamorphic rock reservoirs is fractures^{3,4,5,6}. Therefore, through core observation and imaging logging, many scholars have finely characterized fractures, including the length, width, density, opening, dip of fractures, and the angle between ground stress and the strike of fractures (to judge whether the fracture is easy to open during fracturing), and have studied the formation, evolution stages and classification of fractures and whether there is fill and the nature of the fill^{1,2,3,5,7,8,9}. At present, research on fractures in metamorphic rock reservoirs is relatively mature^{3,9}. It is undeniable that fractures have a very important impact on the gas production of metamorphic rock reservoirs. However, in addition to fractures, there are many pores and microfissures that are invisible to the naked eye and cannot be identified by image logging in metamorphic rock reservoirs^{9,10}. Similar to shale, these microscopic pores and microfissures can also become reservoir spaces and flow channels for natural gas, and fracturing technology makes production of natural gas from smaller pores possible¹¹. Therefore, it is necessary to study the microscopic pores in metamorphic rock reservoirs. The combination of microscopic pores and macroscopic fractures can provide a more comprehensive understanding of the reservoir space in metamorphic rock reservoirs.

The pore characteristics of the metamorphic rock reservoir are relatively underexplored^{12,13}. At present, research on metamorphic rock reservoirs is mainly based on fracture characterization and well logging

identification, and there are few studies on the pore characteristics of metamorphic rock reservoirs and the factors that control them^{6,9}.

Considerable controversy continues over the factors controlling the pore structure of metamorphic rock reservoirs. Xia et al. propose that the degree of metamorphism has a great impact on reservoir properties¹⁴, and Zhu et al. suggest that the lithology of metamorphic rocks is a core factor controlling reservoir formation and the preservation of reservoir space¹⁵. Han et al. suggest that the main factors controlling metamorphic reservoir development are temperature, lithology, minerals, dissolution, faults, and paleogeomorphology¹. The research of Liu et al. has focused on rocks that have undergone contact metamorphism, and they conclude that the properties of metamorphic rocks are mainly controlled by lithology and diagenesis before intrusion¹⁶. Previous studies that have conducted research on reservoir pore characteristics have used mainly qualitative methods. In this study, we selected the cores of metamorphic rock reservoirs with underdeveloped macroscopic fractures using a combination of qualitative descriptions (thin section analysis, thin sections and scanning electron microscopy) and quantitative analysis (high-pressure mercury intrusion and nitrogen adsorption-desorption) to comprehensively analyze the pore characteristics of reservoirs and explore the factors controlling the pore characteristics of the metamorphic rock reservoir in the central paleo-uplift belt of the Songliao Basin in an attempt to provide ideas for improving the evaluation system of metamorphic rock gas reservoirs and provide guidance for the exploration of metamorphic rock gas reservoirs.

Geological Setting

The Songliao Basin is an important petroliferous basin in northeastern China that has three major structural sequences: a depression sequence, a faulted sequence, and the basement. A large number of oil fields, represented by the Daqing Changyuan superlarge oilfield, and a large number of natural gas fields, represented by the Xujiaweizi gas field, have been discovered in the depression sequence^{17,18}. However, the exploration level of hydrocarbon resources in the basement of the Songliao Basin is still very low and is still in its infancy.

The investigated districts are located in the central paleo-uplift belt, which is located between the Xujiaweizi fault depression and the Gulong fault depression in the north (Fig. 1-a) and is a buried hill-like uplift zone formed on a basement containing thrust folds. The strata below the second member of the Dengloulou Formation are absent above the basement, and the Dengloulou Formation directly overlaps it.

In the three main salients in the central paleo-uplift belt, namely, the Wangjiatun salient, Zhaozhou salient and Changde salient, three risk wells were developed: the LT1, LT2 and LTX3 wells (Fig. 1-a). Among them, wells LT1 and LT2 reveal a metamorphic rock reservoir in the basement and have good natural gas shows. The daily gas production rate of the metamorphic rock reservoir in the LT1 well is $1.0 \times 10^4 \text{ m}^3$, and that of the LT2 well is $3.6 \times 10^4 \text{ m}^3$ ¹⁸, which shows that the basement of the central paleo-uplift belt has

good exploration potential and is an important strategic area for hydrocarbon resources in the Songliao Basin^{19,20}.

Petrological Characteristics Of Metamorphic Rock Reservoir

The lithologies revealed by the LT1 and LT2 wells are mainly metamorphic rocks. The basement revealed in the LT1 well can be divided into three lithological members: the lower member is mica schist, the middle member is mylonite, and the upper member is chlorite schist (Fig. 1-b). The basement revealed in the LT2 well can be divided into two lithological members: the lower member is mylonite, and the upper member is unmetamorphosed granite (Fig. 1-c). This article focuses only on metamorphic rocks. Two samples were taken from each lithological member. The specific information is shown in Table 1.

Table 1 Sample list

Sample ID	Well	Depth (m)	Lithology	Protolith	Metamorphism
1	LT1	2778.67	chlorite schist	andesite	dynamic
2	LT1	2780.5	chlorite schist	andesite	dynamic
3	LT1	3374.44	mica schist	clastic rock	regional
4	LT1	3444.33	mica schist	clastic rock	regional
5	LT1	2986.97	mylonite	granite	dynamic
6	LT1	2989.77	mylonite	granite	dynamic
7	LT2	2961.7	mylonite	granite	dynamic
8	LT2	2964.4	mylonite	granite	dynamic

3.1 Chlorite schist

The chlorite schist (Samples 1 and 2) in the LT1 well has a blasto-pilotaxitic texture (Fig. 2-a) and schistose structure (Fig. 2-b) and is mainly composed of quartz (approximately 15 vol.%), feldspar (approximately 35 vol.%), chlorite (approximately 35 vol.%), biotite (approximately 5 vol.%), epidote (approximately 5 vol.%) and calcite. The minerals show directional alignment. Residual andesite phenocrysts and residual plagioclase can be observed (Fig. 2-b); albites have an ocellar structure (Fig. 2-a). Therefore, the protolith of chlorite schist is andesite that experienced dynamic metamorphism.

3.2 Mica schist

The mica schist (Samples 3 and 4) in well LT1 has a porphyritic crystalloblastic texture, fine granular lepidoblastic texture and schistose structure and is mainly composed of quartz (approximately 25 vol.%), feldspar (approximately 25 vol.%), chlorite (approximately 12 vol.%), mica (including biotite and muscovite, approximately 35 vol.%) and garnet (approximately 3 vol.%). Quartz and feldspar grains are

separated by directionally aligned biotite and muscovite. Faint blastopsammitic structure (Fig. 2-d) can be observed. The abundance of micas implies that the rock contained mud, so the protolith was a clastic rock, and the metamorphism was regional.

3.3 Mylonite

The mylonite (Samples 5, 6, 7, and 8) in the LT1 and LT2 wells has a blastogranitic texture, deformation lamella and mica fish (Fig. 2-e) and is mainly composed of quartz (approximately 35 vol.%), plagioclase (approximately 35 vol.%), potash feldspar (approximately 25 vol.%) and muscovite (approximately 2 vol.%). Perthite porphyroclasts (Fig. 2-f) can be observed, and their edges consist of fine quartz that has been dynamically recrystallized and oriented, retaining the granitic structure of the protolith. The feldspar grains are subhedral, the quartz grains are allotriomorphic, and there are no signs of transport. In summary, the protolith was a granite, and the metamorphism was dynamic.

Methods

4.1 Field emission scanning electron microscopy (FE-SEM)

Field emission scanning electron microscopy (FE-SEM) experiments were carried out at the Test Science Experiment Centre of Jilin University. The microstructural morphology of the metamorphic rocks was observed using JSN-6700F equipment. The samples were cut into slices with a length and width of 1 cm and 1 mm thickness and subjected to ion polishing. All images were obtained under a high vacuum mode with an 8 kV voltage. The working distance was approximately 10 mm.

4.2 High-pressure mercury intrusion (HPMI)

High-pressure mercury intrusion (HPMI) experiments were conducted with a Micromeritics AutoPore IV 9520 system at the Beijing Centre for Physical and Chemical Analysis. The maximum intrusion pressure was 30000 psia (206.8 MPa), corresponding to a pore throat diameter of 6.6 nm. The experimental process was as follows: samples were loaded into the core chamber and vacuum pumped for 1 h. After mercury had filled the core chamber, measuring valves and balance valves were opened. Then, mercury was injected gradually under an applied pressure to measure the capillary pressure. Once a maximum pressure of 30000 psia was reached, the pressure started to decrease progressively, and mercury was extruded from the sample. Capillary pressure curves were derived by Micromeritics AutoPore IV 9520 software. The pore size distribution (PSD) was calculated according to the Washburn equation. The laboratory procedure followed Standard GB-T 21650.1–2008.

4.3 Nitrogen adsorption-desorption experiments

Nitrogen adsorption-desorption experiments were carried out at the Test Science Experiment Centre of Jilin University. Prior to adsorption measurements, all metamorphic rock samples were prepared by sieving to a size of 50–80 mesh and then weighing 2–6 g per sample. The samples were dried at 200°C for 6 h in a vacuum oven to remove moisture and volatile gases from the rocks. The Micromeritics

ASAP2020 automatic device was used in the experiment, measuring the gas adsorption volume over the relative equilibrium adsorption pressure (P/P_0) range of 0.01–0.99, and the determinations of adsorption isotherms and outgassing were carried out in a liquid nitrogen environment.

Results

5.1 Microscopic pore types and morphological characteristics

Clay minerals can be identified by scanning electron microscopy. The chlorite schist contains many chlorites (Fig. 3-a), and the mica schist has the most types of clay minerals, including biotite, chlorite and a small amount of montmorillonite (Fig. 3-e), while mylonite has only a very small amount of chlorite.

Figure 3-c, 3-d and 3-h are all quartz particle surfaces. V-shaped holes can be observed in the chlorite schist, and the quartz particles are largely broken (Fig. 3-c), indicating that the chlorite schist formed mainly by mechanical effects during the process of rock formation. The mica schist has little evidence of mechanical effects during the process of rock formation, and although V-shaped holes can be seen (Fig. 3-f), the number of holes is small. Many scales are warped and separated from the carrier and have a tendency to spall (Fig. 3-d). Although these scales may also be debris formed in the grinding process of thin sections, their number is much greater than those in the chlorite schist (Fig. 3-c) and mylonite (Fig. 3-h), and the scales are small; thus, they can be considered scaly spalling (a typical characteristic of chemical dissolution effects²¹). Irregular dissolution pits are also observed, so the mica schist was mainly chemically dissolved during the process of rock formation. The mylonite has obvious conchoidal fractures (Fig. 3-h); therefore, mechanical effects were clearly predominant during the process of rock formation.

Based on previous studies^{14,22} on the classification of metamorphic rock reservoir space and this study, the reservoir space of the metamorphic rock reservoir in the central paleo-uplift belt can be divided into the following four types: intergranular pores, dissolved pores, structural microfractures and weathering microfractures (Table 2). The main reservoir space in the chlorite schist is in the form of intergranular pores and weathering microfractures; the main reservoir space in the mica schist is in the form of intergranular pores and dissolved pores; and the main reservoir space in the mylonite is in the form of dissolved pores, weathering microfractures and structural microfractures.

Table 2 Types and characteristics of reservoir spaces in the metamorphic rock reservoir from the central paleo-uplift belt of the Songliao Basin.

Reservoir space types	Origin	Characteristics
intergranular pores	primary intergranular pores in protolith and pores formed among metamorphic mineral	angular, with a small pore size, visible under a scanning electron microscope
dissolved pores	leaching, dissolution by formation fluid	generally development along fractures, irregular shape
structural microfractures	microfractures formed under tectonic stress	irregular, extending far
weathering microfractures	formed by physical weathering and breaking along the schistosity plane	linear, funnel-shaped, developed in schist

5.2 Characteristics of high-pressure mercury porosity

HPMI and nitrogen adsorption-desorption have proven to be effective methods for characterizing the pore structures of porous media^{23,24}. The PSD that can be detected by HPMI is between 7.1 nm and 208 μm , and the PSD that can be detected by nitrogen adsorption is between 0.858 nm and 233.913 nm²⁵. For the characterization of pore structures less than 200 nm, nitrogen adsorption-desorption is more accurate than HPMI. Therefore, the HPMI method is used to characterize pores larger than 200 nm, and the nitrogen adsorption method is used to characterize pores smaller than 200 nm²⁶.

Figure 4 presents the high-pressure mercury capillary curves of schist and mylonite. The figure shows that the mercury entry curve changes from slow to steep, indicating more large pores and fewer small pores. The curve is generally linear, indicating poor pore sorting. The calculated mercury intrusion parameters are shown in Table 3. The average porosity of schist is 1.46%, the average porosity of mylonite is 1.00%, and the porosity of schist is higher than that of mylonite.

The displacement pressures of the metamorphic rock samples are very low. For the schist, the maximum value is 0.0643 MPa, and the average value is 0.0425 MPa. The maximum displacement pressure of the mylonite is only 0.0255 MPa, and the average is 0.0232 MPa (Table 3), which is significantly less than that of the schist, indicating that the mylonite has a larger maximum pore throat and higher permeability²⁷. The maximum mercury saturation can reflect the heterogeneity of the reservoir. The maximum mercury saturation of schist is 73.64% on average, while that of the mylonite is 84.32% on average (Table 3), reflecting that the schist is more heterogeneous and that mylonite is more homogeneous. The retreat mercury curves of the schist and mylonite are linear, and a large amount of mercury is withdrawn at the first point of pressure reduction. After this point, there is very little mercury withdrawal. The withdrawal efficiencies are very low, with values of 30.25% for the schist and 24.84% for the mylonite on average (Table 3).

Table 3 Parameters of high-pressure mercury intrusion for metamorphic rock samples

Sample ID	Porosity (%)	Displacement pressure (MPa)	Maximum pore throat (μm)	Withdrawal efficiency (%)
1	1.51	0.0643	19.40	11.25
2	1.98	0.0275	45.32	7.68
3	1.63	0.0370	33.72	6.43
4	0.73	0.0412	29.77	43.28
Schist	1.46	0.0425	32.05	17.16
Average				
5	1.28	0.0255	48.87	13.34
6	1.07	0.0241	51.75	20.54
7	0.91	0.0240	51.93	23.48
8	0.73	0.0192	64.85	26.91
Mylonite	1.00	0.0232	54.35	21.07
Average				

The pore distribution of metamorphic rock reservoir samples is shown in Fig. 5. It can be seen from the figure that the chlorite schist has the narrowest pore size distribution, the mylonite has a wider pore size distribution, and the mica schist has the widest pore size distribution. This shows that the heterogeneity of the mica schist is the strongest.

5.3 Characteristics by nitrogen adsorption-desorption experiments

Figure 6 presents the adsorption isotherms of the samples. When the relative pressure is very low, the nitrogen exhibits micropore filling and monolayer adsorption. As the relative pressure increases, the nitrogen molecules in the first layer reach saturation, and a relatively obvious inflection point appears in the isotherm adsorption curve (point B in Fig. 6, taking Sample 3 as an example, reflecting the existence of macropores and mesopores); then, multilayer adsorption occurs in the metamorphic rocks. As the relative pressure increases, the number of nitrogen molecule adsorption layers gradually increases. When the relative pressure rises to a certain value, the nitrogen gas in the pores starts to condense²⁵. None of the samples show a horizontal plateau at a relative pressure close to 1, illustrating that metamorphic samples still contain a range of macropores that cannot be analyzed by nitrogen adsorption-desorption experiments²⁸. The adsorption quantity in the schist is much higher than that in the mylonite, indicating that the schist has more pore space than the mylonite.

The type of adsorption isotherm and the shape of the hysteresis loop can indicate the pore type of a porous medium²⁶. According to the International Union of Pure and Applied Chemistry (IUPAC)

classification, the schist has type II adsorption isotherms, and the mylonite has type III adsorption isotherms. The branch of the adsorption curve and the branch of the desorption curve do not coincide, forming a hysteresis loop that is caused by processes involving adsorption into and desorption from mesopores²⁴. According to the IUPAC classification, the schist and mylonite have both H3-type loops and H4-type loops, indicating that the sample pore types are mainly flat, slit-like and ink bottle-shaped.

The results of nitrogen adsorption require the use of different data processing methods, such as the Brunauer-Emmett-Teller (BET)^{29,30}, Barrett-Joyner-Hallenda (BJH)³¹ and density functional theory (DFT) models³². Nitrogen adsorption can yield three important parameters: specific surface area, average pore diameter and specific pore volume (Table 4). The BET method is suitable for calculating specific surface area, the BJH method is suitable for calculating average pore diameter, and the DFT method is suitable for calculating specific pore volume²⁵. The specific pore volume of the schist is greater than that of the mylonite, which is consistent with the HPMT results. The specific surface area of the schist is also greater than that of the mylonite, while the average pore size is smaller than that of the mylonite.

Table 4 Nitrogen adsorption parameters of metamorphic rock samples

Sample ID	Lithology	Specific surface area (m ² /g)	Average pore diameter (nm)	Specific pore volume (cm ³ /g)
1	schist	4.3059	5.917	0.0085
2	schist	1.6785	9.974	0.0049
3	schist	2.8611	12.683	0.0074
4	schist	0.8726	10.72	0.00271
average value of schist		2.4295	9.824	0.00588
5	mylonite	0.4557	30.635	0.0021
6	mylonite	0.3062	45.375	0.00168
7	mylonite	0.218	46.763	0.00024
8	mylonite	0.781	45.626	0.00028
average value of mylonite		0.4402	42.100	0.00108

The BJH model cannot provide a realistic description of the filling of micropores or even smaller mesopores³³, so we applied the DFT molecular model adsorption branch due to its applicability in determining the PSD at both the micropore (pore sizes < 2 nm) and mesopore (pore sizes between 2 nm and 50 nm) scales^{26,34}. Figures 7 and 8 show the PSDs of the samples based on the DFT theory, clearly illustrating the PSD below 200 nm, filling the gap of insufficient detection range and accuracy from HPMT.

The PSD curve of the schist exhibits multimodal characteristics, with several maximum pore diameter values larger than 2 nm (Fig. 7). The mylonite has almost no pores smaller than 10 nm, and its pores are mainly distributed between 50 nm and 200 nm (Fig. 8).

Discussion

6.1 Pore fractal characteristics

Fractal geometry has a strong ability to describe the irregular or fragmented shapes of natural features as well as other complex objects that traditional Euclidean geometry fails to characterize³⁵. The fractal dimension (D) is the key parameter in fractal geometry and provides a systematic approach to quantifying irregular patterns^{36,37}. The fractal Frenkel-Halsey-Hill (FHH) model has been proven to be the most effective method for analyzing the fractal behavior of porous media³⁸. The FHH model, which has been widely recognized and used^{1,26,38,39}, can be described using the following Eq. 3⁸:

$$\ln \frac{V}{V_0} = \text{constant} + (D - 3) \ln \left(\ln \frac{P_0}{P} \right)$$

where V is the quantity of adsorbed nitrogen gas at equilibrium pressure P, V₀ is the volume of monolayer coverage and P₀ is the saturation pressure.

According to the equation, on the plot of lnV vs ln (ln (P₀/P)), the slope of the straight line should be equal to D-3. The FHH plots of metamorphic samples are shown in Fig. 8 and clearly show that the slopes of the FHH graphs of all samples are not uniform, so there is more than one fractal dimension. Based on previous studies^{1,26,38,39}, the nitrogen adsorption isotherm can be divided into two main regions with a relative pressure of 0.5 (P/P₀ = 0.5), obtaining two fractal dimensions, D1 and D2. Region 1 is the monolayer-multilayer adsorption in which the dominant force is van der Waals, and D1 can be calculated from the slope of the line in region 1. Region 2 is the capillary condensation regime, where the surface tension is the dominant force, and D2 can be calculated from the slope of the line in region 2^{40,41}. D1 represents fractals from pore surface areas generated by surface irregularities, while D2 characterizes fractals related to pore structures that are controlled by the composition and pore parameters. Higher fractal dimension D1 correlates to more irregular surfaces that provide more space for CH₄ adsorption. Higher fractal dimension D2 represents higher heterogeneity of pore structure and higher liquid/gas surface tension that reduce CH₄ adsorption capacity. The calculation results (Table 5) show obvious regularity. The D1 of the schist is lower than that of the mylonite; the average D1 of the schist is 2.1193, while the average D1 of the mylonite is 2.6782, indicating that the mylonite has more irregular surfaces. The D2 of the schist is higher than that of the mylonite; the average D2 of the schist is 2.6643, while the average D2 of the mylonite is 2.4543, indicating that schist has a higher pore heterogeneity of pore structure. The mylonite has a higher D1 and lower D2, indicating that it has more natural gas reservoir space and stronger natural gas adsorption capacity, making it a better reservoir.

6.2 Formation process of the metamorphic rock reservoir

The U-Pb zircon dating results from our research team (Table 6) reveal that the concordant age of the chlorite schist is 131.3 ± 8.5 Ma, indicating that the andesitic protolith formed during the deposition of the upper Shahezi Formation and lower Yingcheng Formation in the Cretaceous. The concordant age of unmylonitized granite in the upper part of the LT2 well is 160.7 ± 1.9 Ma, which is Late Jurassic; the concordant age of granitic mylonite in the LT1 and LT2 wells is 264.2 ± 2.6 Ma, indicating that the formation of the granitic protolith occurred in the middle-late Permian.

Table 5 Calculation results for fractal dimensions

Sample ID	Lithology	D1	D2
1	schist	1.5999	2.7665
2	schist	2.2144	2.6488
3	schist	2.3455	2.6015
4	schist	2.3172	2.6403
average value of schist		2.1193	2.6643
5	mylonite	2.5595	2.4791
6	mylonite	2.7089	2.4540
7	mylonite	2.7316	2.4242
8	mylonite	2.7489	2.4599
average value of mylonite		2.6872	2.4543

The concordant age of the the mica schist in Well LT1 is 275.2 ± 2.6 Ma, indicating that the diagenesis of its clastic protolith occurred no earlier than 275.2 Ma (early Permian). Because the upper granite formed in the middle-late Permian, the formation of the clastic rock should have occurred earlier than the middle-late Permian, so the formation time of the clastic rock can be constrained to the early-middle Permian.

Table 6 Reservoir chronological results for the central paleo-uplift belt

Lithology	Protolith	Chronology	Formation time of the protolith
chlorite schist	andesite	131.3 ± 8.5 Ma	late Shahezi period-early Yingcheng period in Cretaceous
granite		160.7 ± 1.9 Ma	Late Jurassic
mylonite	granite	264.2 ± 2.6 Ma	middle-late Permian
mica schist	clastic rock	275.2 ± 2.6 Ma	early-middle Permian

According to the structural background of the Songliao Basin and the four chronological test results, we hypothesize that the formation process of the metamorphic rock reservoir in the central paleo-uplift belt can be divided into the following four stages (Fig. 9):

(1) Formation and weathering of Permian protoliths

In the early-middle Permian, thick marine strata, i.e., the protoliths of the mica schist, were deposited (Fig. 9-a), and granitic magma then intruded in the middle-late Permian to form granite, forming the protolith of the mylonite. From the end of the Permian to the Early Triassic, the collision of the northeastern block and the North China Craton occurred along the Sauron-Siramulun-Changchun suture zone; this process uplifted the crust, and the strata underwent erosion (Fig. 9-b)⁴².

(2) Formation and weathering of Mesozoic protoliths

Previous studies have found Triassic strata in the Songliao Basin⁴³. The Middle Triassic strata began to be deposited, and the Late Jurassic granitic magma later intruded (Fig. 9-c). In the Cretaceous period, when the Huoshiling Formation was deposited, during the low-angle subduction of the Pacific Plate towards the Asia-Europe Plate, basement faults became active⁴⁴, and the Xuxi fault began to form (Fig. 9-d)⁴⁵. During the Cretaceous Huoshiling-Shahezi depositional period, weathering and erosion occurred. During the late Shahezi-early Yingcheng depositional period in the Cretaceous, lava erupted to form andesite, representing the protolith of the chlorite schist (Fig. 9-e).

(3) Metamorphic stage

The development of the basement reservoir in the central paleo-uplift zone of the Songliao Basin was related to the activity of the Xuxi fault²⁰. Large-scale activity of the Xuxi fault occurred during the Shahezi-Yingcheng depositional period⁴⁵, and the surrounding rocks were metamorphosed. Andesite in the upper part underwent both brittle deformation and ductile deformation under strong stress. At the same time, chlorite was produced by alteration of hornblende and formed the chlorite schist. The granite in the middle part also experienced brittle and ductile deformation but more ductile deformation. The clastic rocks in the lower part were buried deeper, and the increase in temperature triggered regional

metamorphism. The mud was transformed into biotite, muscovite, garnet and chlorite, and the feldspar and quartz particles became directionally aligned, forming the mica schist. From shallow to deep, the degree of ductile deformation gradually increased, and the deep rock layer experienced regional metamorphism, which conforms to the behavior of dynamic metamorphic rock (fault rock)⁴⁶. The Late Jurassic granite was not metamorphosed because it was far from the fault (Fig. 9-f).

(4) Weathering and deep burial

There is an unconformity between the Yingcheng Formation and Dengloulou Formation in the Cretaceous, which is called the T4 unconformity surface. In the Yingcheng-Dengloulou period, the strata underwent weathering and erosion. Because the Yingcheng Formation had a weak resistance to weathering and erosion, all of these rocks were removed. However, the chlorite schist is relatively resistant to weathering and erosion and was only partially removed, forming a weathering crust (Fig. 9-g). Subsequently, the overlying Cretaceous Dengloulou Formation was deposited (Fig. 9-h).

6.3 Factors controlling microscopic pore characteristics of the metamorphic rock reservoir in the central paleo-uplift belt

(1) Effect of metamorphism on microscopic pore characteristics

(2) For andesite (the protolith of the chlorite schist), dynamic metamorphism can cause deformation and fracturing, increasing the reservoir space, while fine-grained chlorite is produced by alteration of hornblende and fills previously formed pores and fracture pores; thus, dynamic metamorphism has both constructive and destructive effects on the reservoir.

For granite (the protolith of the mylonite), dynamic metamorphism causes the originally dense granite to break and crack, having a constructive effect on the reservoir.

For clastic rocks (protoliths of the mica schist), regional metamorphism causes the minerals to recrystallize and directionally align, reducing the original pores and having destructive effects on the reservoir.

(3) Effect of structural location on microscopic pore characteristics

The influence of the structural position on microscopic pore characteristics is mainly reflected in the reservoir space derived from physical weathering. The chlorite schist and mylonite in the LT1 well and Late Jurassic granite in the LT2 well are weathered and eroded, so they all have weathering fractures, while the mica schist was below the surface, so no weathering fractures are observed.

(4) Effect of the protolith on microscopic pore characteristics

Many microscopic pore characteristics are related to the protolith characteristics.

Andesite is formed by the eruption and rapid cooling of magma on the surface. Due to different volatiles, the vesicles in andesite are unevenly distributed, and phenocrysts are unevenly distributed in the matrix. The rock can also undergo varying degrees of weathering and leaching at the surface. Therefore, andesite is not homogeneous. Clastic rocks are formed by cementing various types of debris with different grain sizes; thus, they are also not homogeneous. In contrast, granite forms underground where the temperature is higher. The temperature decreases slowly, and it takes a long time for granite to crystallize, so it is relatively homogeneous. Judging from the results, both HPMI and fractal algorithms reveal that the schist is more heterogeneous than the mylonite.

The protoliths of the schist, whether andesite or clastic rock, were loose and porous, while the protolith of the mylonite was granite, which is very dense and basically nonporous. The HPMI experiments show that the schist has a higher porosity than the mylonite, and the nitrogen adsorption tests show that the adsorption quantity and specific pore volume of the schist are much higher than those of the mylonite. Although metamorphism reduced the pore space in the schist and increased the pore space in the granite, the original pore space of the protoliths largely controls the final pore space.

Generally, among the three kinds of protoliths, argillaceous siltstone has the most clay minerals, andesite has the second highest amount, and granite has the lowest amount of clay minerals. According to the SEM observations, the mica schist has the most clay minerals, including biotite, montmorillonite and chlorite. The chlorite schist contains a large amount of chlorite, and the mylonite contains only a very small amount of chlorite.

Quartz and feldspar are both brittle granular minerals that are prone to cracking under tectonic stress⁹, while dark-colored minerals are more elastic, have high ductility and are not prone to cracking^{10,15}. Therefore, microfractures have developed in the mylonite, but microfractures cannot be found in the schist.

In addition, the protoliths controlled the metamorphic histories of the rocks to some extent. The granite in the middle part and the clastic rocks in the lower part are continuous vertically, and both formed in the Permian, but their metamorphic styles are different. The clastic rocks contain many impurities, such as matrix material, mica and chlorite debris, which are prone to alteration. In contrast, the granite mineral composition is basically quartz and feldspar, which are simple, relatively stable and not prone to alteration. Temperature was the dominant factor in the metamorphism of the schist, which overall experienced regional metamorphism, while stress was the dominant factor in the metamorphism of the mylonite and caused partial dynamic metamorphism.

In summary, the microscopic pore characteristics of the metamorphic rock reservoir are controlled by the metamorphic style, structural location and protolith, among which the protolith was the most important controlling factor.

Conclusions

1. Three metamorphic rock reservoir lithologies are revealed in wells LT1 and LT2: the chlorite schist formed by dynamic metamorphism from an andesitic protolith; the mylonite formed by dynamic metamorphism from a granitic protolith; and the mica schist formed by regional metamorphism from clastic protoliths.
2. The reservoir space can be divided into four types: intergranular pores, dissolved pores, structural microfractures and weathering microfractures.
3. The PSDs of the schist and mylonite are different.
4. Compared with the schist, the mylonite has less reservoir space, stronger homogeneity, larger pore size, smaller specific surface area, more natural gas reservoir space and stronger natural gas adsorption capacity.
5. The formation process of the reservoir can be divided into four stages: formation and weathering of Permian protoliths, formation and weathering of Mesozoic protoliths, metamorphism and weathering and deep burial.
6. The microscopic pore characteristics of the metamorphic rock reservoir are controlled by the metamorphic style, structural location and protolith, among which the protolith is the most important controlling factor.

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Figures

Figure 1

(a) Structural map of the top of the basement in the central paleo-uplift zone and the distribution of well locations (modified from Du et al., 20171); (b) basement stratigraphic column of the LT1 well; (c) basement stratigraphic column of the LT2 well. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research

Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Photomicrographs showing the petrological characteristics of the metamorphic rock reservoir: (a) sample 1, chlorite schist (-); (b) sample 1, sample 2, chlorite schist (+); (c) sample 4, mica schist (+); (d) sample 3, mica schist (-); (e) sample 5, mylonite (+); (f) sample 7, mylonite (+) Note: The designations employed

and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Types of reservoir space in metamorphic rock samples. (a) chlorite schist, 1; (b) chlorite schist, 2; (c) chlorite schist, 2, with quartz surface; (d) mica schist, 5, with quartz surface; (e) mica schist, 5; (f) mylonite, 6; (g) mylonite, 5; (h) mylonite, 7, with quartz surface. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Capillary pressure curve of the metamorphic rock reservoir sample.

Figure 5

Pore distributions of metamorphic rock reservoir samples through high-pressure mercury injection.

Figure 6

N₂ gas adsorption/desorption isotherms.

Figure 7

(a) PSD analysis of schist samples using DFT methods; (b) PSD analysis of mylonite samples using DFT methods

Figure 8

FHH plots for the metamorphic samples.

Figure 9

Inferred formation process of the metamorphic rock reservoir.