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Study on the relationship between lithology and reservoir characteristics of Yingcheng Formation in the southern Songliao Basin

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Abstract. In order to deeply understand the relationship between the microstructural characteristics of volcanic reservoirs and the lithology of volcanic rocks, it provides important theoretical significance for the effective development of volcanic reservoir oil and gas fields. The microscopic characteristics of the volcanic reservoirs of the Yingcheng Formation in the Songliao Basin were analyzed by means of rock section determination, pore structure parameters analysis and casting thin section analysis. The results show that the target layer has low porosity and permeability, and the volcanic pore structure of different lithologies is different. Volcanic lava generally develops original gas pores, phenocryst dissolved pores, matrix dissolved pores, and tectoclase, while volcanic clastic rocks generally have developmental dissolution pores as the main feature. The micro-heterogeneity of volcanic reservoirs is generally strong, and the development of tectonic fractures is an important factor in changing the reservoir performance of volcanic rocks.

1. Introduction

As an unconventional oil and gas reservoir, volcanic rocks have been in exploration for more than 100 years abroad. In recent years, China has made major breakthroughs in the exploration of volcanic rocks such as the Songliao Basin, the Erlian Basin and the Junggar Basin [3]. In particular, a number of volcanic reservoirs have been discovered in the Junggar Basin in northern Xinjiang, showing great development potential [5]. The Songliao Basin is a large Mesozoic sedimentary basin in eastern China with a fault-depression double-layered stratigraphic filling sequence [7]. With the deepening of the exploration and development of volcanic gas reservoirs, the Lower Cretaceous Yingcheng Formation volcanic rocks have become an important target stratum [2]. The research focus on volcanic reservoirs is gradually studied from the macroscopic laws of stratigraphy, lithology and lithofacies, and gradually turned to the fine-grained characteristics of sequence interface genesis, reservoir description and rock geochemistry [6].

The core problem of volcanic gas reservoir exploration is reservoir prediction, and whether it is the key to reservoir formation depends on whether the reservoir space develops [4, 9]. This paper discusses the relationship between volcanic reservoir spatial characteristics and volcanic lithology from the geochemical characteristics of reservoir volcanic rocks, casting thin sections, pore characteristic parameters analysis and physical properties of rocks, which provides important theoretical significance for oil and gas exploration in volcanic reservoirs in the future.



2. Petrological characteristics of volcanic rocks

The volcanic rocks in the Songliao Basin are complex in lithology and have many types of rocks. The Yingcheng Formation in this area has a large burial depth, high formation temperature, large lithological changes, strong heterogeneity, and often accompanied by fault development. All these have brought considerable difficulties to the exploration and development of natural gas. In order to further improve the exploration and development efficiency of the volcanic gas reservoirs in the Yingcheng Formation of Songliao basin, it is necessary to further study the lithological characteristics of the volcanic rocks in the Yingcheng Formation. In this study, the results of the main element analysis are shown in (Table 1). The SiO₂ content in the southern part of the Songliao Basin ranges from 55.72% to 78.57%, and the total alkali (Na₂O+K₂O) content ranges from 4.17% to 14.29%, and the TiO₂ content is between 0.23% and 0.99%. The variation of total iron content ranges from 1.56% to 6.38%, indicating that the volcanic rocks in this horizon are dominated by medium-acid volcanic rocks. A graphical representation of the variation of SiO₂ on major elements in volcanic rocks (Figure 1). In general, the content of most major elements (MgO, Fe₂O₃, CaO, Al₂O₃, TiO₂, P₂O₅) in volcanic rocks is positively correlated with SiO₂ content, indicating that the magma may undergo crystallization differentiation.

Table 1. analysis of the composition of major elements (%) in Yingcheng formation of southern Songliao Basin.

	CS1	CS103	CS105	CS1-1	CS1-2	CS3	W21	DS5	DS7	DS9
Na ₂ O	4.11	4.72	1.56	2.67	6.06	4.19	6.68	6.19	4.01	6.78
MgO	0.13	0.51	1.02	0.28	0.03	0.13	0.70	1.85	0.43	1.25
Al ₂ O ₃	12.11	19.22	11.15	13.25	6.11	14.46	18.98	18.75	16.27	20.35
P ₂ O ₅	0.01	0.02	0.01	0.01	0.01	0.02	0.2	0.21	0.07	0.39
K ₂ O	4.88	9.57	3.15	7.35	4.63	4.92	4.61	2.37	5.79	4.08
CaO	0.43	0.08	7.38	0.09	0.37	1.72	1.42	4.36	0.97	2.76
TiO ₂	0.24	0.50	0.23	0.46	0.29	0.36	0.51	0.80	0.35	0.99
MnO	0.06	0.19	0.24	0.21	0.09	0.22	0.04	0.09	0.04	0.05
TFe ₂ O ₃	3.19	6.38	3.81	3.85	2.83	5.62	3.12	5.45	1.56	3.79
LOI	1.08	3.06	7.82	1.98	1.03	2.00	2.76	1.32	2.35	3.00
SiO ₂	73.64	55.72	63.22	69.6	78.57	66.27	60.57	58.77	68.36	56.22
Total	99.87	99.96	99.59	99.75	100.01	99.91	99.58	100.16	100.2	99.66

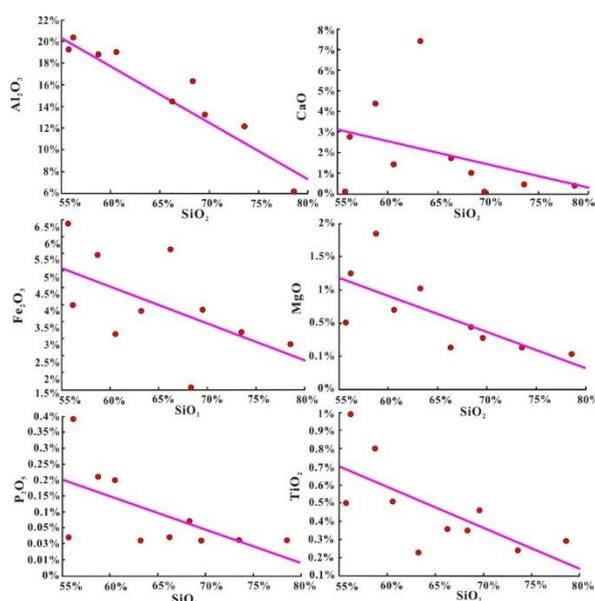
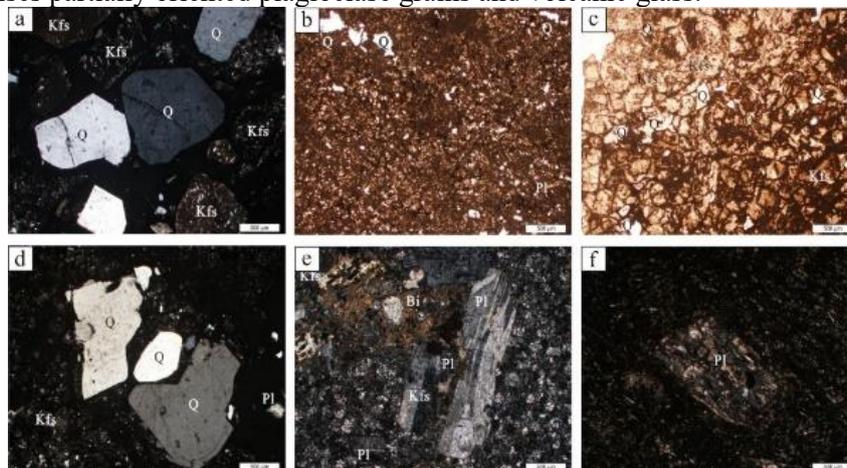


Figure 1. Relationship between silicon oxide and main element of volcanic rocks in Yingcheng Formation.

Core observation and rock section identification results show that there are mainly six types of volcanic rock samples obtained. Rhyolitic debris–crystal welded tuffs (Figure 2a) that comprise quartz and feldspar crystals (~70%), ash (~20%), and debris (~10%). Quartz crystals are xenomorphic, display granular textures, and are locally corroded. Tuff (Figure 2b) that comprise crystals (~5%) cemented by ash (~95%), display tuff textures, and contain block structures. Crystals comprise mainly angular–subangular quartz and feldspar with grain sizes of <0.5 mm. Rhyolite (Figure 2c), with a porphyritic and a block structure. The phenocrysts are mainly composed of feldspar and quartz, and the content is about 10%. Rhyolitic crystal tuffs (Figure 2d), which are composed of quartz and feldspar crystals (~25%) cemented by ash and fine-grained quartz particles (~75%). Quartz crystals are xenomorphic, granular and locally fragmented. Feldspar crystals are granular and highly altered. Rock debris is rare and is derived mainly from rhyolite. Dacite rock (Figure 2e), with a porphyritic structure, the phenocryst content is about 10%, and the matrix content is about 90%. The phenocrysts are mainly composed of plagioclase, quartz, alkaline feldspar and biotite. Andesites (Figure 2f), the quartz grains are subangular–subrounded. Hornblende grains are long and columnar and locally display dark colors. The matrix (~85%) comprises partially oriented plagioclase grains and volcanic glass.



a. CS1 well, Rhyolitic debris-crystal welded tuff, 3574.00m; b. CS103 well, Tuff, 3726.57m; c. CS1-1 well, Rhyolite, matrix-dissolved pores, 3727.90m; d. CS1-2 well, Rhyolitic crystal tuff, 3671.15m; e. DS7 well, Dacite, 2435.50m; f. DS9 well, andesites, 2010.60m;

Figure 2. Microscopic image of the volcanic rock under the Yingcheng Formation.

3. Reservoir spatial characteristics

The study area comprises mainly intermediate–acidic volcanic rocks that were erupted during the fault-depression phase. These volcanic rocks represent a significant reservoir in the region. As a result of the faulting control, volcanic rocks are exposed over only a relatively small area, although a variety of lithologies occur. The primary pores in the volcanic reservoirs of the Yingcheng Formation are unfavorable for hydrocarbon storage. However, the development of various secondary dissolution pores and fractures during late-stage dissolution and tectonic activity greatly enhanced the reservoir performance of the volcanic rocks.

3.1 Analysis of pore-permeability characteristics of volcanic rocks

Volcanic rock reservoir is more complex than sedimentary rock, and the reservoir has different microscopic pore structure characteristics. In-depth study of the microscopic pore structure characteristics of the reservoir has implications for the reservoir's reservoir capacity and Seepage mechanism. For the developmental characteristics of volcanic rock heterogeneity in space-time, the pore structure parameters of volcanic rocks obtained by mercury,

Table 2. Microscopic pore structure parameters of volcanic reservoirs.

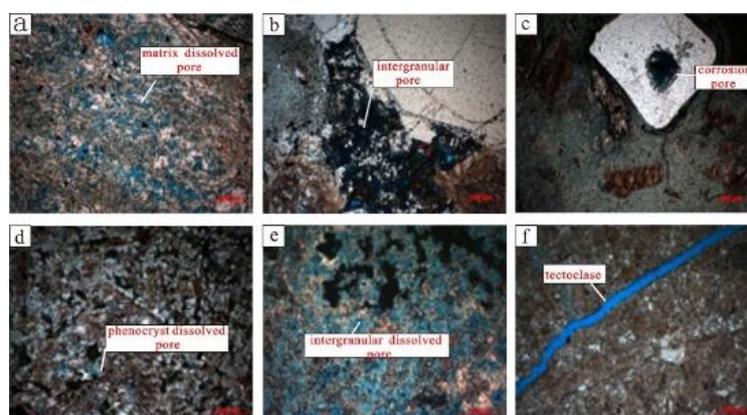
Well	Formation	Lithology	Face rate %	Coefficient of sorting	Uniformity coefficient	Porosity %	Permeability md
CS1	K1yc	Rhyolitic debris-crystal welded tuff	0.02	5.06	0.73	5.4	0.011
CS103	K1yc	Tuff	0.26	11.83	0.48	29.3	9.25
CS105	K1yc	Dacite	0.24	6.65	0.58	2.3	0.0077
CS1-1	K1yc	Rhyolite	2.79	8.84	0.52	13.6	1.22
CS1-2	K1yc	Rhyolitic crystal tuff	0.02	0	1	6.4	0.0086
CS3	K1yc	Dacite	0.2	10.06	0.75	4.7	0.0035
DS7	K1yc	Dacite	1.1	7.36	0.73	3.3	322
DS9	K1yc	Andesite	0.13	4.05	0.75	3.3	0.071

penetration data are mainly used to analyze the relationship between porosity and permeability. Target stratum porosity is mainly concentrated in less than 10%, only CS103 well tuff and CS1-1 well rhyolite porosity were 29.3%, 13.6%, tuff is obviously better than the lava reservoir property, which is associated with the structure characteristics of rock and tuff with tuff structure, mainly composed of crystal and ash, high ash content, intergranular pore development, arrange loose structure, so the highest porosity and permeability. Followed by rhyolite, since the rhyolite often develops the original gas pores and devitrification pores, the value of porosity is also large. The permeability values are mainly concentrated below 1mD, and the pore permeability values are small. Only partially affected by the fracture, the permeability is large (Figure 3f). Under the condition that the porosity is only 3.3%, the permeability reaches 322mD. Generally, the volcanic reservoir of the Yingcheng Formation in the study area has the characteristics of low porosity and low permeability.

The parameters used to characterize the microscopic heterogeneity of volcanic rock reservoirs are mainly pore radius, pore-throat separation coefficient, uniformity coefficient, coordination number, average pore shape factor, average pore-throat ratio and structure coefficient [8]. The variation law of pore structure can be studied by using this parameter. From the statistical data (Table 2), the average pore radius ranges from 6.61 μ m to 17.21 μ m, and the reaction pore development is better; The sorting coefficient reflects the uniformity of the pore throat size. The uniformity of the pore throat size is, the better the sorting property is. On the contrary, the worse the sorting property is. When the sorting property is greater than 3, the sorting property is extremely poor. The sorting coefficient of the sample shows that the sorting is very poor; The average uniformity coefficient is 0.69, which is small overall, indicating that the pore homogeneity of the target layer in the study area is poor; The pore throat coordination number is an important parameter reflecting the pore connectivity. Although some rock samples have a small porosity, the permeability may be very high as long as there is a throat connected to it. In summary, it can be seen from the microscopic parameters of volcanic pore characteristics that volcanic reservoirs are characterized by relatively high heterogeneity, which is one of the difficulties in the exploration of volcanic reservoirs.

3.2 Reservoir porosity and fracture characteristics

Through the analysis of 10 cores in the Songliao Basin and the observation of the cast thin section, the volcanic reservoir space types in the study area are divided into two categories: primary reservoir space and secondary reservoir space. Further, according to the morphological characteristics, the reservoir space is subdivided into primary pores, secondary pores, primary fractures and secondary fractures.



a. CS1-1 well, Rhyolite ,3727.90m; b. CS1-2 well, Rhyolitic crystal tuff,3671.15m; c. CS1 well, Rhyolitic debris-crystal welded tuff, 3574.00m; d. CS3 well, Dacite, 3020.11m; e. CS103 well, Tuff, 3726.57m; f. DS7 well, Dacite, 2435.50m;

Figure 3. Casting thin-section images of rock samples.

Primary pores include original air hole, corrosion pores, and intergranular pores. The original air hole is mainly developed in the volcanic lava. It is the pores formed by volatiles escaping due to the sudden drop of pressure in the process of condensation and crystallization after magma erupts from the surface, and most of them are filled by minerals in the later stage, thus affecting the reservoir performance of this fault depression. In the volcanic lava quartz and feldspar plaque often develops a molten hole (Figure 3c), the corrosion hole is due to the formed phenocryst, which is sprayed on the surface in the deep magma, the pressure is rapidly reduced but the temperature rises instantaneously. The phenocryst partially suffers from the pores formed by the erosion, and the edge of the pores is smooth and is basically filled by the same period of magmatic melt. In volcanic clastic rocks, volcanic rock crystals and cuttings are re-deposited by handling, and the contact between the particles is not tight, and a small amount of intergranular pores remain after burial (Figure 3b). Secondary pores include phenocryst dissolved pores in volcanic lava (Figure 3d), matrix-dissolved pores (Figure 3a) and intergranular dissolved pores in volcanic clastic rocks (Figure 3e), which are a series of dissolutions of volcanic rocks during diagenetic evolution. The shape of the pores is irregular, and the dissolution pores are the most important pore types for improving volcanic reservoirs.

The primary cracks include joint cracks or explosion cracks. During the magma upwelling process, the crystallized minerals are formed by sudden pressure drop and temperature change cracking or high-pressure blasting inside the lava body. Secondary cracks include dissolution seam and tectoclase, which are developed in various volcanic rocks. The developmental scale of tectoclase varies, and some can develop giant cracks that cut through the entire volcanic rock mass, and also have microcrack of several millimeters. tectoclase often develop in strips, and the cracks can be parallel or interwoven. Most of the tectoclase are nearly flat, which can cut through the particles and phenocryst and extend farther (Figure 3f). The structural dissolution joint can connect the existing reservoir space and is an important channel for deep oil-gas migration.

4. Volcanic rock reservoir control factors

Reservoir heterogeneity is the most important factor affecting oil recovery ratio, and the relationship between micro-heterogeneity and reservoir structure and effective development is inseparable [8]. The lithology of volcanic rocks determines the development and distribution of primary pores of the reservoir. The porosity and fracture development degree of different lithology vary greatly, which determines the physical properties of the reservoir.

The magma erupted from the surface of the volcanic eruption, magmatic eruption and condensation contraction to form primary pores. After diagenesis of volcanic rocks, they are exposed to the earth's surface through leaching process and weather-worn. When the crustal movement is buried underground, hydrothermal alteration and filling will occur, and the primary pores will be transformed to form

secondary pores. The tectonics trigger volcanic eruptions and form large volcanic rocks, which form the basis of volcanic reservoirs. Tectonic movement can cause cracks in dense volcanic rocks. The denser and more brittle the volcanic rocks, the easier the tectoclase are formed. The tectonic fracture itself is an important seepage channel for natural gas in volcanic reservoirs. It is also an important channel for groundwater and organic acids, providing a prerequisite for the dissolution of minerals and facilitating the formation of secondary pores. These cracks not only connect the isolated original gas holes, but also increase the storage space of volcanic rocks.

5. Conclusion

The reservoir space of the Yingcheng Formation volcanic reservoirs in the southern Songliao Basin is mainly composed of pores and fractures. Volcanic lava generally develops original gas holes, phenocrystal dissolved pores, matrix dissolved pores, and tectoclase, while volcanic clastic rocks generally have developmental dissolution pores as the main feature. The micro-heterogeneity of volcanic reservoirs is generally strong, and the porosity is mainly distributed below 10%. The overall physical properties are poor, and the reservoir has the characteristics of low porosity and low permeability. The tectoclase not only plays a role in connection, but also connects the mutually unconnected pores into effective pores, and the tectoclase itself is also an important type of reservoir space. Therefore, fissure development is an important factor in changing the reservoir performance of volcanic rocks. The particularity of volcanic reservoirs and the special controlled laws of volcanic gas reservoirs make volcanic gas reservoirs an important type of reservoirs for deep exploration in the Songliao Basin. The analysis of the parameters of the pore throat microstructure of volcanic reservoirs is of great significance for the effective exploitation of volcanic oil and gas fields.

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