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Petroleum Geology and Exploration of Deep-Seated Volcanic Condensate Gas Reservoir around the Penyijingxi Sag in the Junggar Basin

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Abstract: Many types of volcanic rock oil and gas reservoirs have been found in China, showing great petroleum exploration potential. Volcanic reservoir also is one of the key fields of exploration in the Junggar Basin and mainly concentrated in the middle and shallow layers, while the deep volcanic rock and natural gas fields have not been broken through. Based on comprehensive analysis of core observation, single well analysis, reservoir description, source rocks evaluation, combined with seismic data and time-frequency electromagnetic technology, multiple volcanic rock exploration targets were identified, and industrial oil and gas flow was obtained in the well SX 16 of the Penyijingxi Sag, western Junggar Basin. It is believed that the deep Permian source rocks have relatively higher natural gas generation potential and volcanic breccia usually have large reservoir space. And the mudstone of the Upper Wuerhe Formation played as the role of caprock. The success of exploration well SX16 has achieved a major breakthrough in natural gas exploration in the Penyijingxi Sag, which has essential guiding significance for the exploration of deep volcanic rocks and large-scale gas exploration in the Junggar Basin.

Keywords: condensate gas; volcanic rocks; Penyijingxi Sag; Junggar basin; Carboniferous



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1. Introduction

Both deep-seated petroleum reservoirs and unconventional petroleum are hotspot for exploration and development [1–3]. And deep-seated petroleum exploration is an important strategic replacement field for oil and gas exploration in China [4,5]. With the deepening of theoretical understanding of high-quality reservoir formation mechanism, deep oil and gas hydrocarbon generation and reservoir formation, deep oil and gas exploration has gradually attracted extensive attention. Volcanic rock is an essential field of oil and gas exploration in China [6,7]. Many types of volcanic rock oil and gas reservoirs have been found in the Songliao, Bohai Bay, Hailar, Erlian, and Sichuan basins of China [8–10], showing great petroleum exploration potential.

In China, as early as the 1970s to 1980s, it was recognized that volcanic rocks can be used as reservoir rocks and volcanic reservoirs such as Huangshatuo, Oulituozi, and Rehetai were successively discovered. The Junggar Basin is one of the large petroliferous basins in northwestern China [11,12]. More than sixty years of petroleum exploration show that the Junggar Basin is rich in oil and poor in natural gas [13]. Volcanic reservoir is one of the key fields of oil and gas exploration in Junggar Basin [14,15]. In the early stage of exploration, many oil reservoirs were found in the northwest margin of the basin [16]. Volcanic oil and gas reservoirs are mainly concentrated in the middle and shallow layers, the deep seated volcanic rock and natural gas fields have not been broken through. In order to find large-scale oil and natural gas reservoirs, based core observation, single well analysis, reservoir description and hydrocarbon source rock evaluation, combined with

seismic data and time-frequency electromagnetic technology, several volcanic rock targets were identified for the deep volcanic rocks in the Penyiingxi Sag of the Junggar Basin. The exploration well was successfully deployed, and high-yield industrial oil and gas flow was obtained, revealing the great potential for oil and gas exploration in deep volcanic rocks, which has essential guiding significance for the exploration of deep volcanic rocks and large-scale gas exploration in the Junggar Basin.

In summary, many types of volcanic rock oil and gas reservoirs have been found in China, showing great petroleum exploration potential. Volcanic reservoir also is one of the key fields of exploration in the Junggar Basin and mainly concentrated in the middle and shallow layers, while the deep volcanic rock and natural gas fields have not been broken through. The study has essential guiding significance for the exploration of deep volcanic rocks and large-scale gas exploration in the Junggar Basin.

2. Exploration History of Volcanic Rocks in the Junggar Basin

Junggar basin is located in the west of China, with Junggar Boundary Mountain in the northwest, Altai Mountain in the northeast and North Tianshan Mountain in the south [17,18]. It is a slightly triangular closed basin with an area of 130,000 km² (Figure 1a,b). It is one of the four major oil-gas basins with oil and gas resources of more than 10 billion tons in China [11,12]. It has been rich in oil and poor in gas for a long time [13,19].

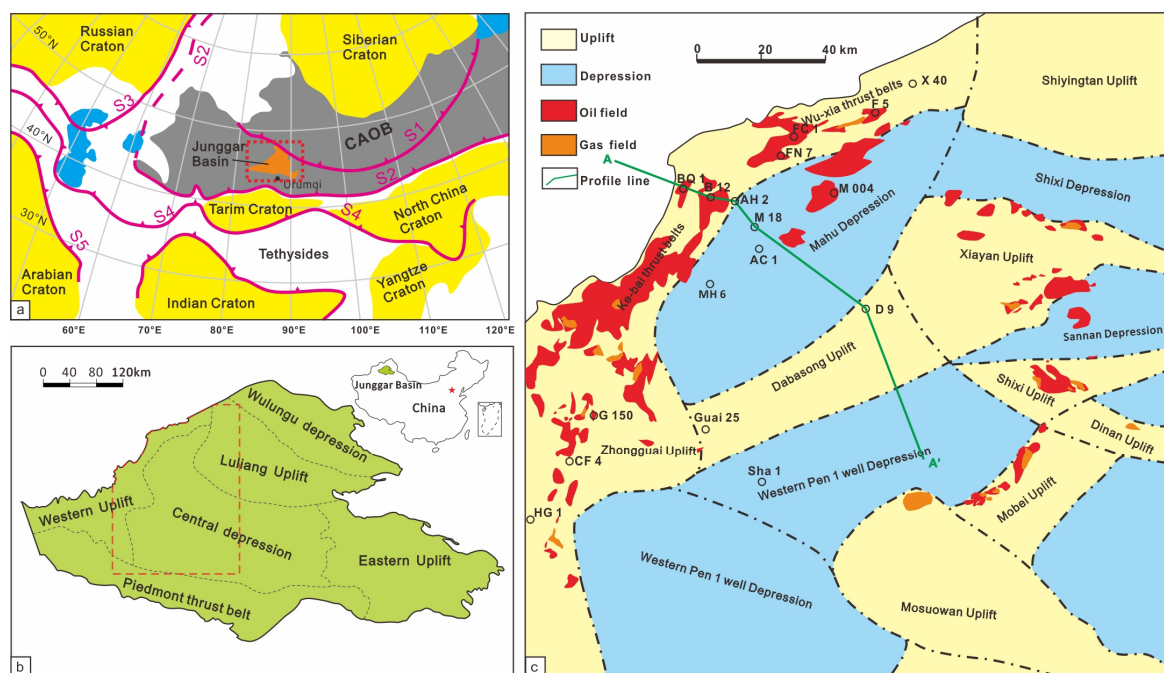


Figure 1. Distribution of structural units, oil fields, gas fields, and sample wells distributions in the northwestern Junggar Basin (After reference [20]). (a) geotectonic setting of the Junggar Basin; (b) tectonic unit of the Junggar Basin; (c) study area tectonic unit and petroleum, exploration well distribution. Reprinted with permission from Ref. [20].

Before 1990, the volcanic exploration in Junggar Basin mostly belonged to the early exploration stage, and the exploration discoveries were mainly oil reservoirs, which were all located in the northwest margin region of the Junggar Basin [20]. From 1990 to 2000, with the continuous improvement of geological knowledge and exploration technology, targeted exploration was carried out in Shixi area and Chepaizi area of Junggar basin [21]. The exploration discoveries were mainly oil and some natural gas. Since 2000, volcanic exploration in Junggar basin has stepped into an accelerated stage, and breakthroughs have been made successively in the Liuzhong Area of the northwest margin [22]. In 2007 and 2008, large-scale breakthroughs in natural gas have been made in the northwest margin,

and significant progress and breakthroughs have been made. The early volcanic exploration in Junggar Basin mainly focused on the middle and shallow layers such as Shixi uplift. Due to the recognition accuracy and engineering technology, the deep layer has not been explored yet.

With the increase of exploration degree, deep volcanic rocks have gradually become the focus of exploration and experienced a tortuous exploration process [23]. In 2006, the Moshen-1 well was deployed and the design well depth was 7380 m. After more than one year of drilling, nearly 400 m tuff was drilled in the Carboniferous system. The gas logging showed good results. Gas invasion occurred during the drilling process of the Carboniferous system, but oil and gas flow could not be obtained during the oil test. Although the exploration of Moshen-1 well did not obtain industrial oil and gas flow, the good gas logging shows increased confidence of deep volcanic rock exploration. In 2015, Datan 1 well was implemented, with a drilling depth of 6226 m. The Carboniferous-Jurassic system has obtained extremely active oil and gas display, with a longitudinal span of more than 2500 m, and no industrial oil flow has been obtained from igneous rocks. In view of the active oil and gas display of well Datan 1, well Yantan 1 was deployed in 2016. Frequent interbedding of tuff andesite and basalt was encountered in Carboniferous, unfortunately there was no oil and gas display in igneous rocks.

In 2016, the exploration focus was adjusted from Dabasong Uplift to the surround of the Penyijingxi Sag, and a comprehensive study on the deep volcanic rocks in the Penyijingxi Sag was carried out. The study shows that the Permian hydrocarbon source rocks have a high degree of deep organic matter thermal evolution and large-scale gas generation potential. And well SX 16 exploration well was deployed for deep volcanic rocks in 2019. Formation testing was conducted in the 4800 m deep andesitic breccia well section of Carboniferous system, and high-yield oil and gas flow was obtained. Since then, a major breakthrough has been made in the exploration of deep volcanic rocks and deep natural gas in the basin.

3. Data and Method

Based on comprehensive analysis of core observation, microscopic slice observation and physical property, combined with logging and seismic data, volcanic reservoirs were distinguished and predicted. Source rocks distribution was defined by seismic data and petroleum filling intensity was defined by the data of grain with oil inclusions. With seismic data and time-frequency electromagnetic technology, multiple volcanic rock exploration targets were identified.

4. Result of Reservoir and Source Rock Characteristics

4.1. Types and Characteristics of Volcanic Reservoir Space

The volcanic reservoir in the Penyijingxi Sag is mainly developed in andesitic and basaltic volcanic rocks, mainly including andesitic cryptoexplosive breccia, andesitic volcanic breccia, andesitic tuff, stomatal andesite, massive andesite, stomatal basalt, and massive basalt. The reservoir space and association law of andesitic volcanic rocks in Shixi area are systematically summarized by using core and cast thin section analysis methods (Figure 2).

Andesitic cryptoexplosive breccia is mainly developed near the volcanic channel. It is formed by blasting the early volcanic rocks in situ during the later magma rising process. The magma filled between the self-broken breccias has poor crystallinity and is easy to dissolve, forming a large number of intergranular solution pores. It is characterized by large dissolution pores, and its shape is limited by the boundary of the self-broken breccias (Figure 2a). Andesitic volcanic breccia and andesitic tuff are formed by volcanic eruption. The volcanic debris is composed of crystal debris and rock debris, and the matrix is volcanic dust. Because volcanic dust is composed of volcanic glass with poor stability, it is prone to devitrification to form intergranular micropores. It is easy to dissolve under the action of fluid, forming a large number of dissolution pores in the matrix (Figure 2b,c).

Stomatal andesite and stomatal basalt are developed in the upper part of lava flow unit, some primary pores are filled by amygdaloid, and secondary dissolution occurs in the later stage, forming a large number of dissolution pores in amygdaloid (Figure 2d,e). In addition, the curved condensation shrinkage cracks between the amygdaloid body and the pore wall are also common in the stomatal andesite and the stomatal basalt, which are formed by the condensation shrinkage of the amygdaloid body (Figure 2f). Massive andesite and massive basalt are developed in the middle and lower part of the lava flow unit, with similar reservoir space characteristics. They are characterized by massive structure, less porosity and lack of primary pores. Under the action of weathering fluid, phenocrysts and matrix can undergo dissolution to a certain extent, forming intracrystalline solution pores (Figure 2g) and matrix dissolved pores with sieve-like distribution (Figure 2h). In addition, structural fractures of massive basalt and andesite are relatively developed (Figure 2i). Structural fractures are formed by regional tectonic stress and deformation. The fractures are generally flat or in micro saw tooth shape (tracking tensional joints), and the filling content is generally not high (Figure 2i). In summary, there are many types of pores in the volcanic reservoir, showing good reservoirs developed in deep-seated volcanic.

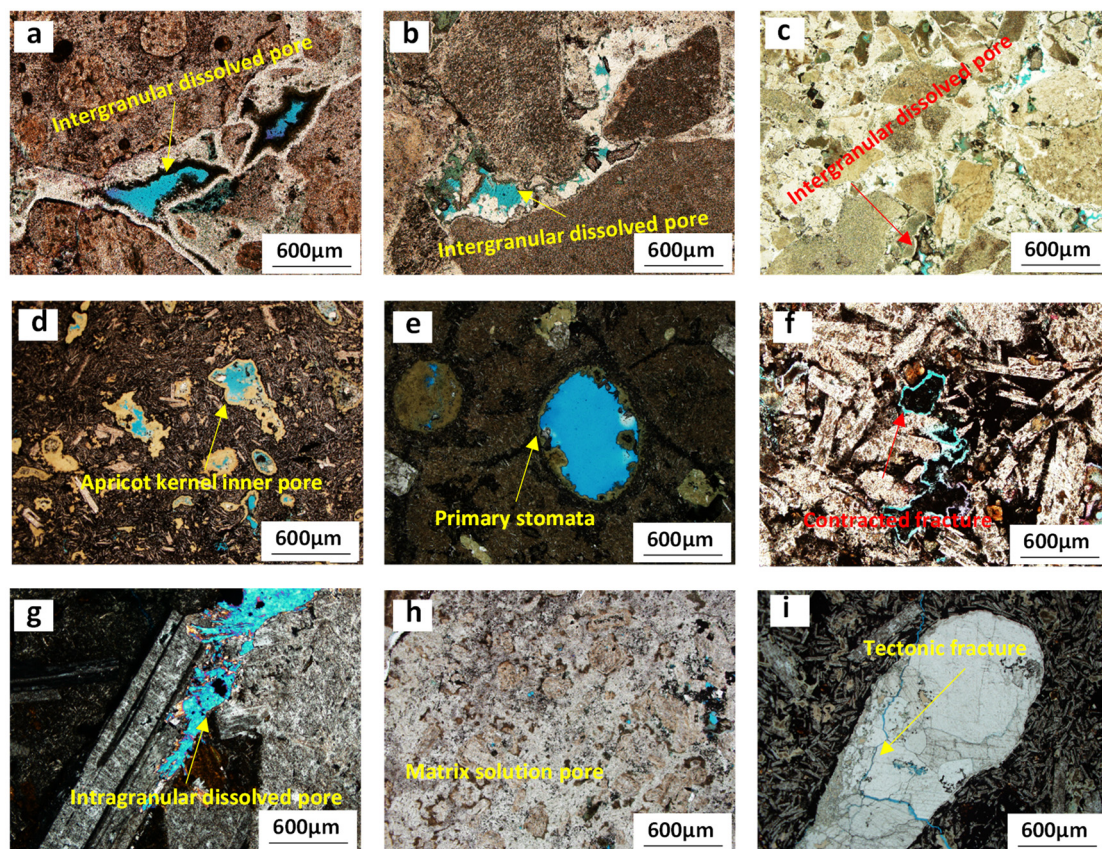


Figure 2. Types and characteristics of volcanic reservoir space around the Penyijingxi Sag. (a) Interparticle dissolution pore of andesitic cryptoexplosive breccia. (b) Interparticle dissolution pore of andesitic volcanic breccia. (c) Matrix solution pore of andesitic tuff. (d) Pore inner stomatal basalt amygdaloid. (e) Pore inner andesite amygdala. (f) Basalt amygdaloid contraction joint. (g) Intracrystalline solution pore of andesite. (h) Andesite matrix solution pore. (i) Structural fracture.

4.2. Physical Property Characteristics of Volcanic Reservoir

The reservoir physical property statistics of volcanic reservoirs with different lithology in the study area are shown in Figure 3. The matrix porosity of andesitic volcanic breccia formed by eruption is between 10 and 20%, and the maximum permeability can reach $100 \times 10^{-3} \mu\text{m}^2$, which is the best reservoir. Stomatal andesite, stomatal basalt, and

andesitic cryptoexplosive breccia have similar physical properties. Their matrix porosity is between 10 and 20% and permeability is $0.1 \times 10^{-3} \sim 1 \times 10^{-3} \mu\text{m}^2$, which is also a relatively favorable volcanic reservoir. The matrix porosity of massive andesite is between 3 and 10% and the seepage rate is $0.01 \times 10^{-3} \sim 1 \times 10^{-3} \mu\text{m}^2$, the reservoir physical property is poor. The porosity of massive basalt matrix is between 1 and 5% and the permeability is $0.01 \times 10^{-3} \sim 0.1 \times 10^{-3} \mu\text{m}^2$, which basically cannot form an effective reservoir. Compared with clastic rocks and dolomitic rocks, the Carboniferous deep volcanic rocks are less affected by compaction, and the widely developed unconformity at the top of the Carboniferous system will significantly improve the physical properties of the reservoir. It is comprehensively considered that the deep volcanic rocks develop large-scale reservoirs.

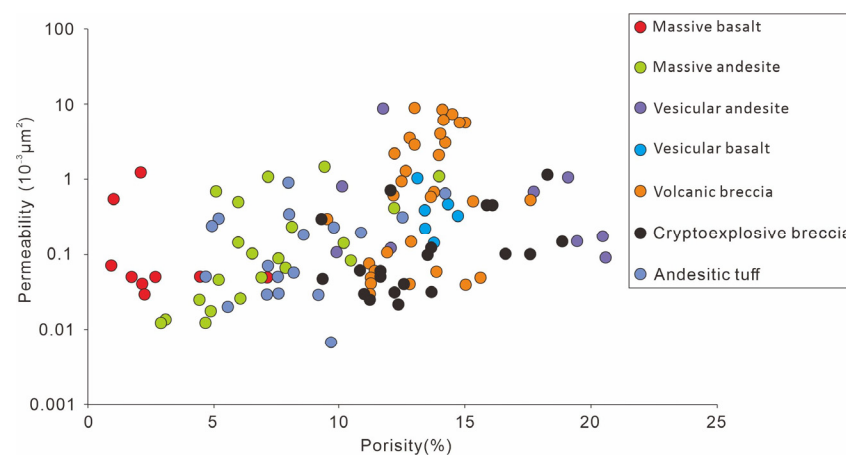


Figure 3. Crossplot of porosity and permeability of volcanic rocks in Shixi area of the Junggar Basin.

4.3. Distribution and Evolution of Petroleum Source Rocks

At present, the Permian source rocks were widely drilled in the Mahu Sag and no well has been drilled in the Penyijingxi Sag. The Permian source rocks in the Mahu Sag have high organic matter abundance and are mainly medium-good hydrocarbon source rocks, with organic matter type II, and are developed from low to high maturity [24]. Through the comparison between Mahu Sag and Penyijingxi Sag, it is considered that the depositional environment of Permian is similar as a whole. It is concluded that two sets of source rocks of the Fengcheng Formation and lower Wuerhe Formation are developed in the Penyijingxi Sag, which is similar to the Mahu Sag.

According to the seismic data, the formation thickness of the Fengcheng Formation and Lower Wuerhe Formation is identified. The mudstone of the Fengcheng Formation and Lower Wuerhe Formation is widely distributed, with a thickness of more than 200 m.

In the Mahu Sag, the burial depth of source rocks of the Fengcheng Formation in the Mahu Sag is mostly less than 6500 m, and decade's years petroleum exploration had confirmed that the source rocks are in the stage of oil generation, and has not entered in the stage of condensate gas generation stage.

From the Mahu Sag to the Penyijingxi Sag, the burial depth of source rocks gradually increases, and the buried depth of Fengcheng Formation source rocks in the Penyijingxi Sag is more than 9000 m. Combined with the burial depth of source rocks and the thermal evolution simulation of organic matter, it is considered that the evolution degree of source rocks in the Lower Wuerhe Formation is dominated by high maturity, mainly in the condensate generation oil and gas and wet gas stages (Figure 4a), and the evolution degree of Fengcheng Formation source rocks is mainly high mature and over mature, mainly in the stage of generating wet gas and dry gas (Figure 4b).

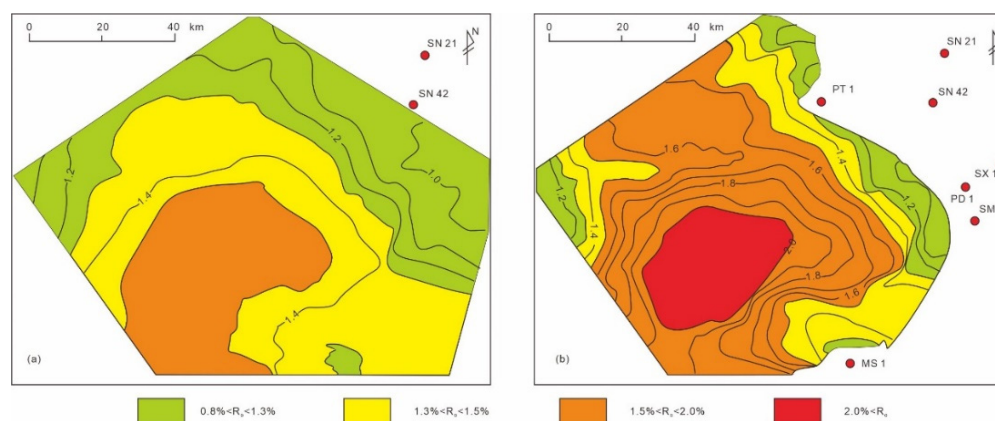


Figure 4. Plane distribution of organic matter maturity (R_o) of Permian main source rocks. (a) R_o of the Lower Wuerhe Formation; (b) R_o of the Fengcheng Formation.

5. Discussion on Petroleum Accumulation and Natural Gas Exploration

5.1. Distribution Model of Volcanic Rocks Reservoir

The Penyijingxi Sag is surrounded by Dabasang Uplift, Xiayan Uplift, Shixi Uplift, Mobei Uplift, and Mosuowan Uplift. According to the lithological characteristics of Upper Carboniferous revealed by drilling, Xiayan Uplift and Dabasang Uplift in the west of Penyijingxi Sag are mainly basic basalt, and tuff, intermediate acid andesite and dacite with a certain thickness are developed. Affected by the ancient landform, some low-lying areas also developed sedimentary volcanoclastic rocks and sedimentary rocks.

The identification of volcanic lithofacies is the basis for establishing volcanic institutions and making high-quality reservoir predictions [25]. Based on core observation, thin section identification, logging data and seismic, the lithology and lithofacies of volcanic reservoir in the Shixi Uplift was classified and identified [25]. The volcanic rocks in Shixi Uplift, Mobei Uplift and Mosuowan Uplift in the east of Penyijingxi Sag are mainly medium acid andesite, dacite and rhyolite, and volcanic breccia and tuff are developed. Under the influence of volcanic mechanism, volcanic lava and pyroclastic rocks are interbedded, as shown in Figure 5. The volcanoes in Shixi Uplift and Mobei Uplift are continental eruptions and do not develop sedimentary pyroclastic rocks and sedimentary rocks. However, thick sedimentary rocks are developed in the upper part of Mosuowan Uplift, and there are sedimentary pyroclastic rocks and sedimentary rock intercalations in the lower volcanic rocks. On the plane, the lithology of the Upper Carboniferous volcanic rocks around the Penyijingxi Sag has obvious cyclicity.

5.2. Oil and Gas Filling Intensity

The industrial oil and gas flow is obtained from the formation testing of well SX 16. And the gas test has the characteristics of low gas/oil ratio, high oil production and high gas production.

The formation testing results of well SX 16 showed that condensates are the primary petroleum type. Through the observation of reservoir thin sections, it is found that the hydrocarbon phases are diverse, with residual black oil (Figure 6a), black brown heavy oil inclusions (Figure 6b), light yellow fluorescent condensate oil and gas (Figure 6c) and black brown gas hydrocarbon inclusions (Figure 6d). Grain with oil inclusions (GOI) is an essential parameter to evaluate the oil and gas filling intensity. It is generally considered that the GOI of oil layer is mostly greater than 5%, the GOI of the oil-water intermediate layer is 1~5%, the GOI of SX16 well is 8%, and the grain with gas inclusion is 4%, revealing a relative stronger oil and gas charging intensity.

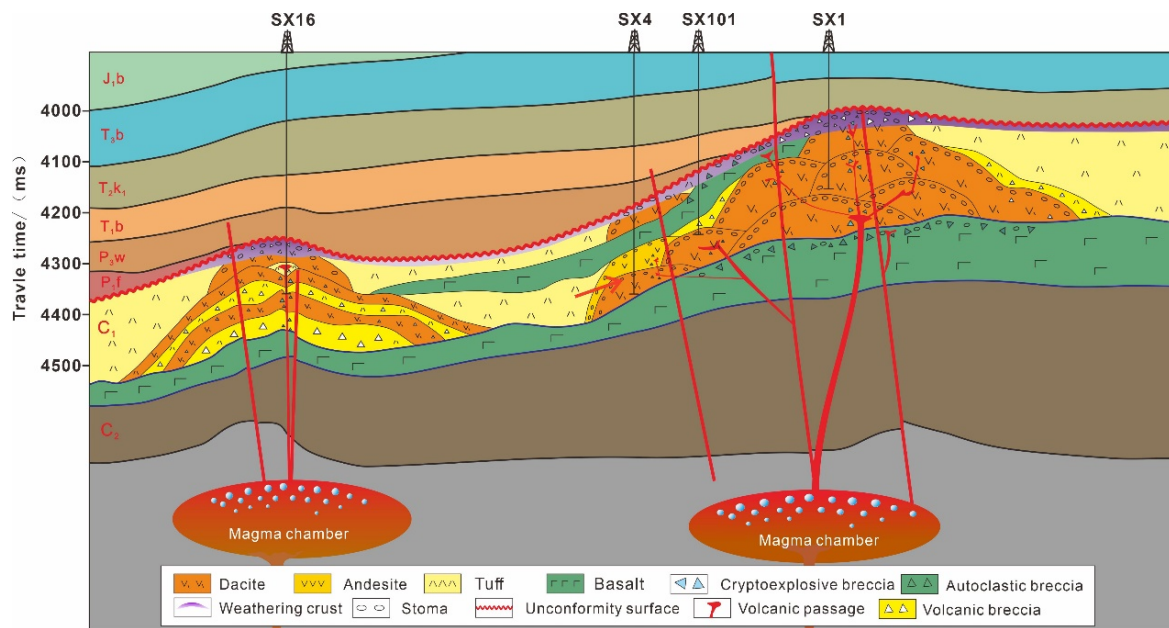


Figure 5. Regional distribution of volcanic rocks in the Penyijingxi Sag and its surroundings.

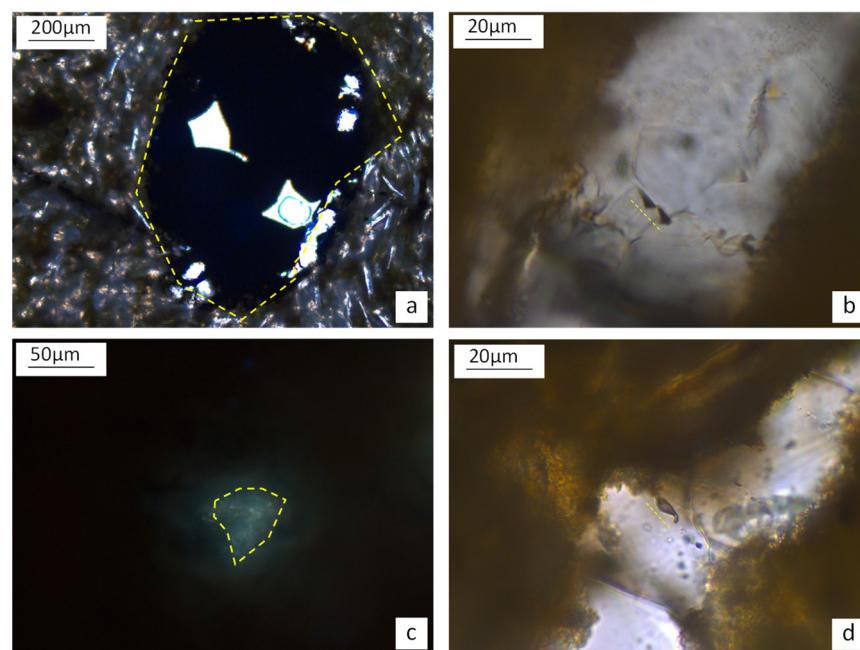


Figure 6. Microscopic characteristics and inclusions characteristics of volcanic reservoir in well SX16. (a), well SX 16, 4806.9 m, black oil, plane polarized light; (b), well SX 16, 4806.9 m, heavy oil inclusion, plane polarized light; (c), well SX 16, 4806.9 m, light yellow, condensate, fluorescent light; (d), well SX 16, 4806.9 m, gas hydrocarbon inclusion, plane polarized light.

5.3. Natural Gas Preservation and Caprock Condition

Most deep-seated oil and gas reservoirs in Junggar basin have experienced multi-stage tectonic movements, and most of hydrocarbon are light oil and natural gas, thus caprock and petroleum reservoir preservation are often one of the key controlling factors. For instance, the oil and gas show of well Datan-1 ranges from the Carboniferous to the Jurassic, with a depth range of more than 2500 m. However, there is and no industrial oil flow has been obtained in the Carboniferous volcanic rocks of well DT 1.

The regionally distributed mudstone of the Upper Wuerhe Formation, Fengcheng Formation are developed on the Carboniferous volcanic rocks, played as the regional cap rocks of volcanic oil and gas reservoirs. The Carboniferous igneous rock of the well SX16 is overlaid with mudstone of the Upper Wuerhe Formation (P_3w) with a cumulative thickness of more than 100 m, which has good preservation conditions and is conducive to the preservation of oil and gas reservoirs (Figure 7).

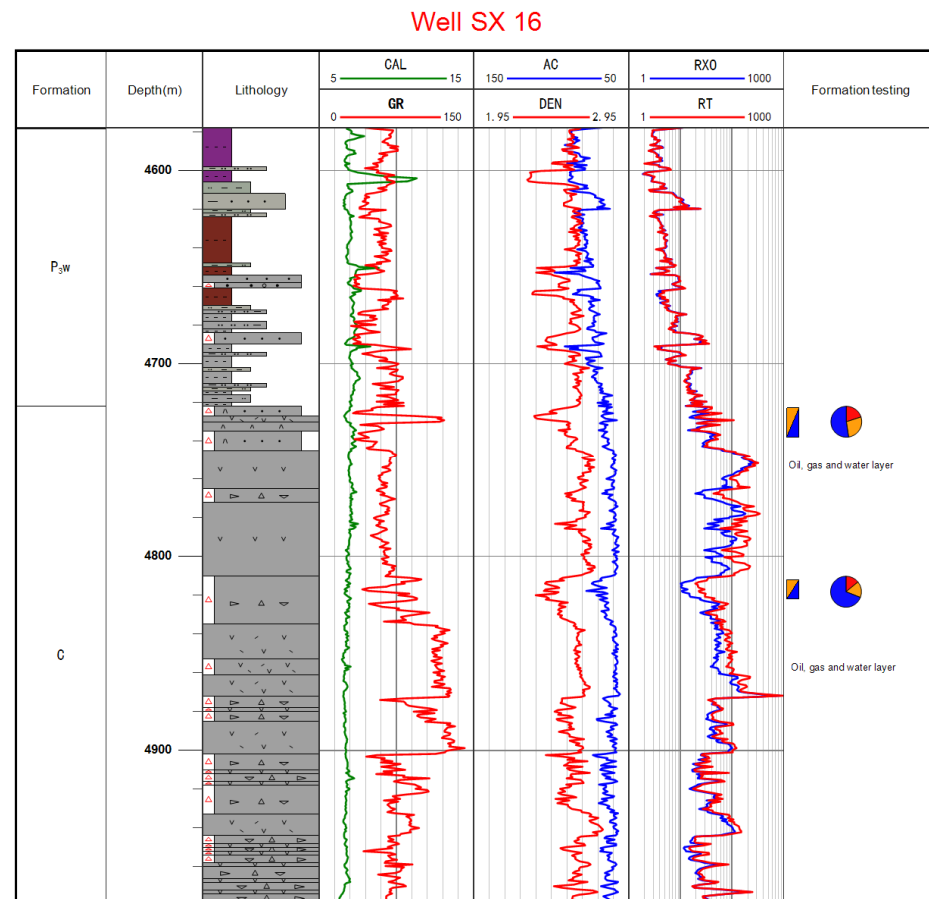


Figure 7. Formation testing results and comprehensive histogram of upper caprocks of well SX 16 around the Penyijingxi Sag.

5.4. Key Techniques for Deep Volcanic Gas Reservoir Exploration

Compared with the medium and shallow layers, the deep oil and gas exploration technology is much more difficult. The improvement of exploration technology has advantageously guaranteed the breakthrough of oil and gas exploration.

Due to the limitations of previous geophysical exploration acquisition techniques and the shielding effect of middle and shallow Jurassic coal rock strata, the existing 3D seismic data have relatively low deep resolution and signal-to-noise ratio (SNR), which cannot meet the requirements for deep volcanic oil and gas reservoir exploration. The progress of 3D seismic acquisition and processing technology for deep volcanic rocks is the key to exploration.

The new seismic imaging technology named “wide frequency, wide azimuth and high-density seismic exploration” have a significant effect on improving the imaging quality [26]. Recently, the “wide frequency, wide azimuth and high-density seismic exploration” new technology had been used to discover exploration target (Figure 8).

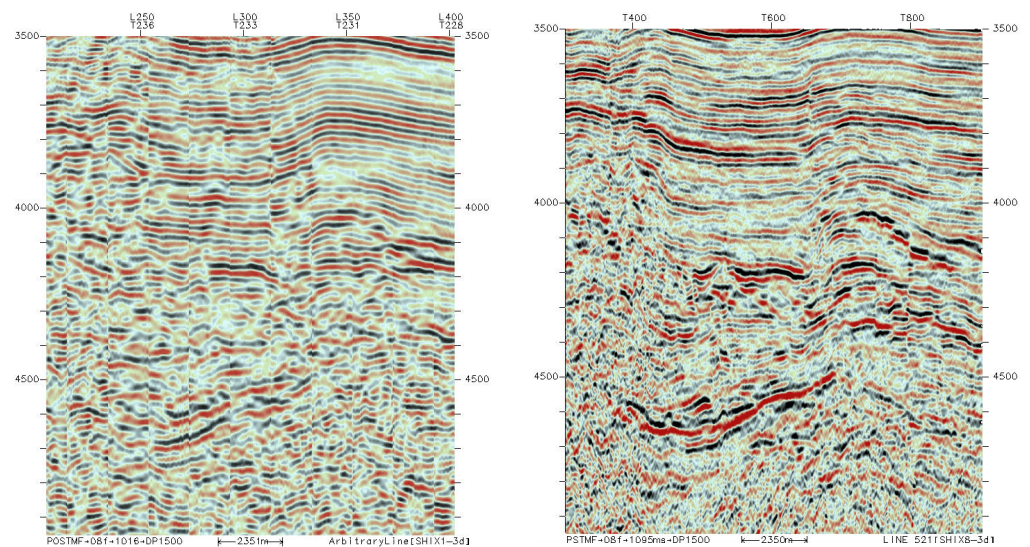


Figure 8. Comparison diagram of seismic profile through well SX16 with conventional (left) and new (right) technology.

Time frequency electromagnetic method (TFEM) is an artificial source electromagnetic detection method based on the principle of electromagnetic induction to observe and study the response field in time domain and frequency domain [27]. This method can effectively eliminate the influence of complex surface conditions and large horizontal variation of underground geological structure, and obtain resistivity and polarizability parameters. It can cooperate with seismic to identify reservoir target lithology, implement geological structure, predict oil, and gas potential, etc. In recent years, this technology has been widely applied in many regions at China and abroad, and has become an indispensable and important means in oil and gas exploration.

Through statistical analysis of the physical property differences between the lithology of different strata and the specific lithology of Carboniferous in the Junggar basin, the resistivity anomaly information template of different types of Carboniferous volcanic rocks is established. Then the abnormal information of time-frequency electromagnetic resistivity and polarizability in SX16 well area is inverted and interpreted (Figure 9). The Carboniferous volcanic rocks were characterized in detail, which effectively improved the drilling success rate of deep and complex volcanic reservoirs and reduced the drilling risk. Through the TFEM exploration application, the distribution of volcanic rocks is determined, which provides a favorable support for the exploration of deep volcanic gas reservoirs.

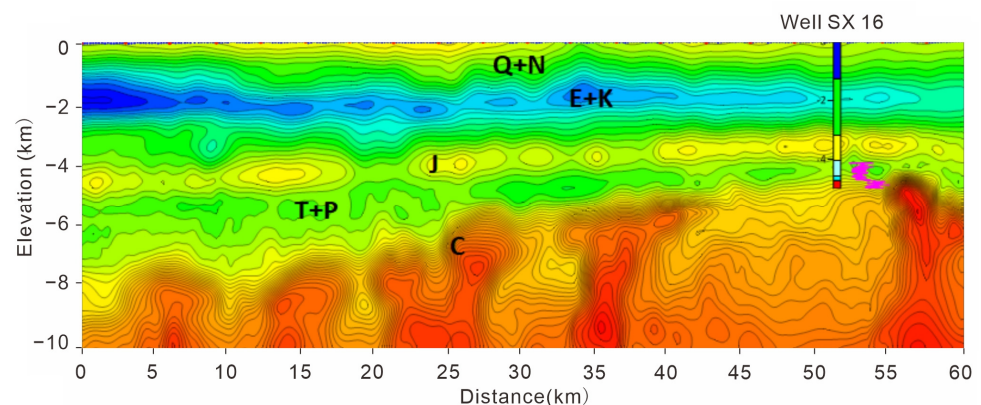


Figure 9. TFEM (time frequency electromagnetic method) profile through well SX16.

5.5. Deep Volcanic Gas Reservoir Exploration Inspiration

The source rocks in the Penyijingxi Sag are characterized by large thickness and wide area, but the source rocks have not been drilled in the study area, and the gas generation capacity of the source rocks is questionable. The great breakthrough which has been made in the exploration of natural gas in deep volcanic rocks confirms that the Permian source rock in the Penyijingxi Sag has the large-scale natural gas generation potential.

The Carboniferous distributed in the Penyijingxi Sag develops large-scale volcanic rocks, and the buried depth gradually increases from north to south. The statistical analysis of physical properties shows that with the increase of depth, the volcanic rocks are supported by the rock framework and volcanic breccia, and the physical properties change relatively little. The exploration breakthrough of well SX16 reveals that the volcanic reservoir has good physical properties, large rock mass thickness, and high gas production, and may become an important exploration area for large-scale natural gas exploration.

6. Conclusions

Based on comprehensive analysis of core observation, single well analysis, reservoir description, and source rocks evaluation, it could be concluded that the source rocks have relatively higher natural gas generation potential and supply a relative stronger oil and gas charging intensity. The deep volcanic rocks may develop large-scale weathered crust reservoirs and the Upper Wuerhe Formation played as the role of caprock and controlling natural gas reservoirs preservation.

Based on comprehensive analysis of petroleum geology elements and the new seismic imaging technology named “wide frequency, wide azimuth and high-density seismic exploration”, a major breakthrough has been made in the exploration of deep volcanic rocks and deep natural gas in the basin. This is the first breakthrough of deep seated gas reservoirs exploration in volcanic reservoir. The success has achieved a major breakthrough in natural gas exploration in the Penyijingxi Sag, which has essential guiding significance for the exploration of deep volcanic rocks and large-scale gas exploration in the Junggar Basin.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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