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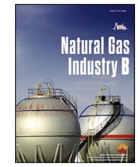

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Research article

Characteristics of volcanic reservoirs and distribution rules of effective reservoirs in the Changling fault depression, Songliao Basin

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Abstract

In the Songliao Basin, volcanic oil and gas reservoirs are important exploration domains. Based on drilling, logging, and 3D seismic (1495 km^2) data, 546 sets of measured physical properties and gas testing productivity of 66 wells in the Changling fault depression, Songliao Basin, eruptive cycles and sub-lithofacies were distinguished after lithologic correction of the 19,384 m volcanic well intervals, so that a quantitative analysis was conducted on the relation between the eruptive cycles, lithologies and lithofacies and the distribution of effective reservoirs. After the relationship was established between lithologies, lithofacies & cycles and reservoir physical properties & oil and gas bearing situations, an analysis was conducted on the characteristics of volcanic reservoirs and the distribution rules of effective reservoirs. It is indicated that 10 eruptive cycles of 3 sections are totally developed in this area, and the effective reservoirs are mainly distributed at the top cycles of eruptive sequences, with those of the 1st and 3rd Members of Yingcheng Formation presenting the best reservoir properties. In this area, there are mainly 11 types of volcanic rocks, among which rhyolite, rhyolitic tuff, rhyolitic tuffo lava and rhyolitic volcanic breccia are the dominant lithologies of effective reservoirs. In the target area are mainly developed 4 volcanic lithofacies (11 sub-lithofacies), among which upper sub-lithofacies of effusive facies and thermal clastic sub-lithofacies of explosion lithofacies are predominant in effective reservoirs. There is an obvious corresponding relationship between the physical properties of volcanic reservoirs and the development degree of effective reservoirs. The distribution of effective reservoirs is controlled by reservoir physical properties, and the formation of effective reservoirs is influenced more by porosity than by permeability. It is concluded that deep volcanic gas exploration presents a good prospect in this area.

Keywords: Songliao Basin; Changling fault depression; Volcanic reservoir; Effective reservoir; Eruption cycle; Reservoir physical properties; Lithology; Lithofacies

1. Geologic setting

With the successive discovery of wells Xushen 1 and Changshen 1 in the Songliao Basin, volcanic reservoirs have become important exploration targets [1]. Volcanic reservoirs are characterized by diverse types and complex formation conditions, and are obviously different from each other in terms of external forms, internal structures and physical characteristics [2], which have brought a lot of difficulties to scientific research and production. In recent years, because the shallow and large rocks with clear features and at favorable locations of the fault depressions have basically been drilled, the volcanic oil and gas exploration is ceaselessly expanded towards deep strata [3]. At present, the study on volcanic rocks in the Songliao Basin mainly focuses on the Lower Cretaceous Yingcheng Formation volcanic rocks in its petrology [4], petrography [5,6], reservoir

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space type and feature [7,8], effects of diagenesis on reservoir formation and hydrocarbon accumulation [9], and reservoir control factors [10,11] and distribution patterns [12]. Only a few researches have been conducted on the deep Lower Cretaceous Huoshiling Formation [13,14]. In 2010, a breakthrough was made in the exploration of the Huoshiling Formation volcanic rocks in the southern Songliao Basin [15]. With the deepening of exploration and study, it has become an important theoretical and practical task to take the fault depression layer of the Songliao Basin as an unified whole to comprehensively study the Yingcheng Formation and Huoshiling Formation volcanic rock sequences and further discuss the relationship between volcanic eruption cycle, lithology, lithofacies and effective reservoir distribution.

In this paper, targeting the Changling fault depression with the largest area and the most abundant resources in the southern Songliao Basin [16], based on relevant 3D seismic data, geologic and well logging data, measured physical property data and well test data of 66 wells (21 of them encountered the Huoshiling Formation) (Fig. 1), and taking the volcanic eruption cycle, lithology, lithofacies and reservoir characteristics of the Yingcheng and Huoshiling Formations as study objects, we quantitatively analyzed the relationship between volcanic eruption cycle, lithology, lithofacies and effective reservoir distribution, in the hope of using the summarized rules having a certain universality to provide a basis for the deep volcanic oil and gas exploration of this area.

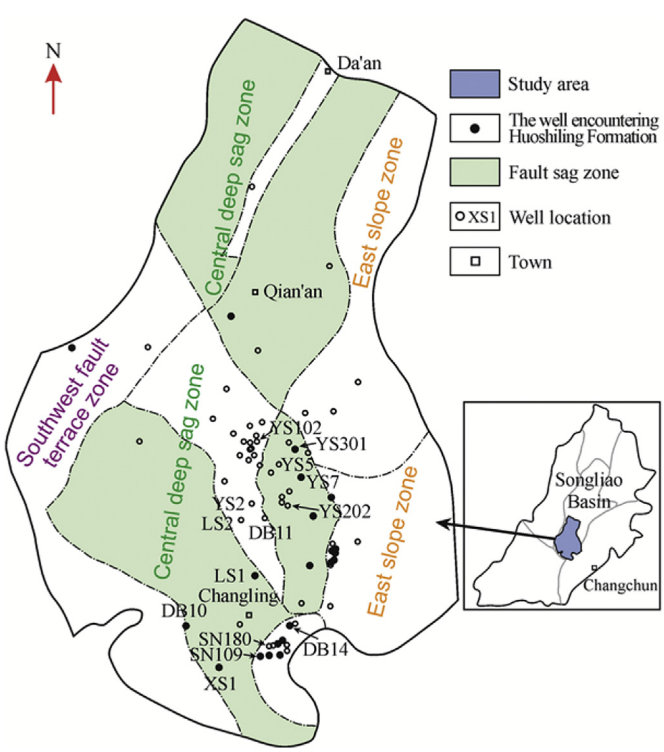

Fig. 1. Changling fault depression location, tectonic zonation and well location.

2. Vertical volcanic sequences

The Songliao Basin has a fault-sag double-layer packing structure that experienced three evolution stages like Huoshiling Formation – Yingcheng Formation fault depression stage, Denglouku Formation – Nenjiang Formation depression stage and Sifangtai Formation – Yi'an Formation tectonic reversion stage [17], and the volcanic rock assemblage relationship is very complicated either in time or in space. Therefore, it is the basis of study on volcanic reservoirs to analyze and confirm the vertical packing sequence and horizontal correlation of volcanic rocks.

The volcanicity in the fault depression stage is featured by multicenter, multicycle and intermittent eruption [18], and the resulted stratigraphic sequence is correlatable in aspects like lithologic association, texture structure and vertical eruption sequence. In this paper, based on the lithologic sequence and association features of the Yingcheng Formation and Huoshiling Formation [13,19], the "dividing formation into members, then into cycles" scheme was used to conduct formation-member-cycle division of individual wells, then, combined with previous research results, the Yingcheng Formation was divided into 3 members and 6 cycles and the Huoshiling Formation into 2 members and 4 cycles from bottom to top respectively (in which, cycle 2 of Member II of the Huoshiling Formation was revealed by drilling in the Wangfu fault depression [13], but not revealed in the Changling fault depression) (Fig. 2). In this way, the basis was laid for dividing volcanic eruption cycle of individual wells.

On the basis of formation-member-cycle division of individual wells, well-seismic correlation was conducted so as to reveal the spatial distribution of volcanic eruption cycles. Firstly, based on the stratigraphic division results of individual wells, horizon calibration, tracing and correlation were conducted on the seismic profile. The seismic reflectance signatures of volcanic sequence boundaries are shown in Fig. 2. Based on which, the lateral tracing and well-to-well correlation of volcanic eruption cycle in the fault depression were conducted. In turn, the seismic reflector tracing was used to verify and adjust the stratigraphic division of individual wells. Both were correlated and confirmed with each other repeatedly, and finally the volcanic sequence correlation of the study area was established. Secondly, based on the seismic trace tracking near wells, the superimposed relationship of volcanic cycles was confirmed. On the basis of formation-member-cycle division of individual wells and calibration and correlation results of corresponding seismic interfaces, based on the superimposition sequence and horizontal correlation of cycles on well tie profile, the termination features and packing patterns of the cycles were confirmed based on different seismic reflectance signatures of them on the seismic profile.

The above methods were used to establish the composite volcanic sequences of the Changling fault depression at fault depression stage, showing that the Huoshiling Formation is dominated by intermediate and basic volcanic eruption, with alkali content increasing gradually in the 4 eruption cycles

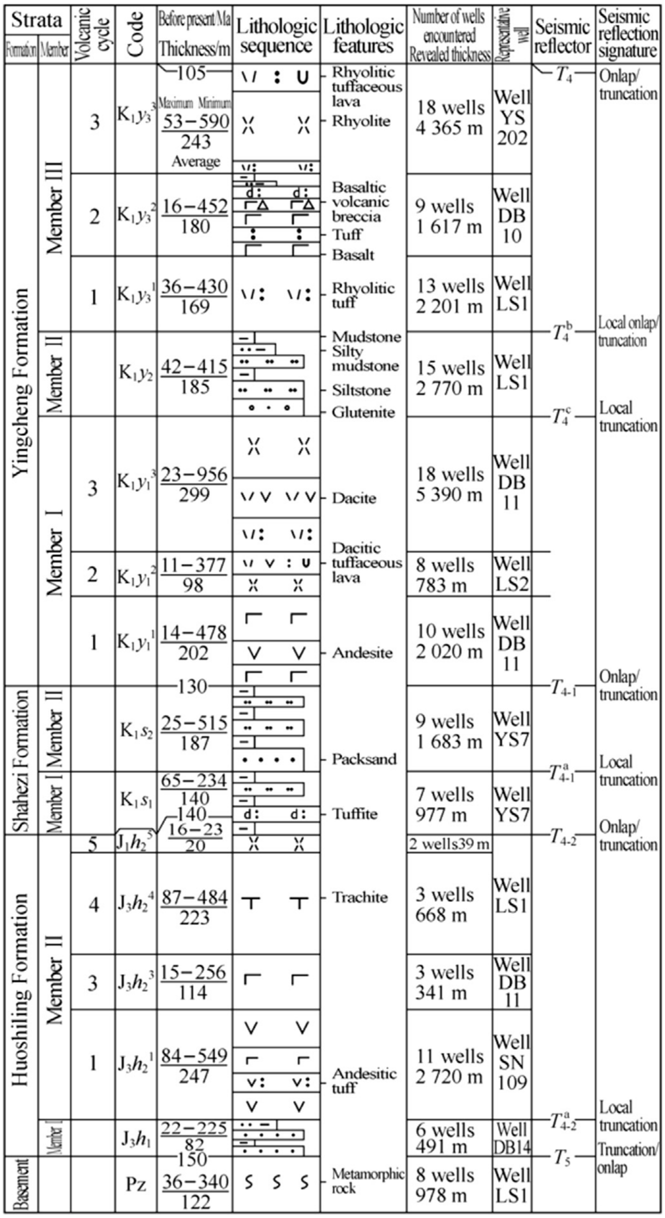

Fig. 2. Composite volcanic sequences of the Changling fault depression. Note: Cycle 2 of Member II of the Huoshiling Formation is dominated by rhyolitic and dacitic volcaniclastic rocks, but acidic volcaniclastic rock association of dacite and dacitic clastic lava is observed, with restricted distribution, only revealed by drilling in the Wangfu fault depression rather than in the Changling fault depression.

from bottom to top, and lithology gradually turning from andesite and basalt interbed into trachyte; the 1st and 3rd Members of the Yingcheng Formation contain three volcanic eruption cycles respectively. The depositional stage of Ying 1 Member is the major volcanic development stage in the area, composing a set of complete intermediate and basic to acidic volcanic eruption process. The Ying 3 Member composes a full rhythm of acidic – intermediate and basic – acidic volcanic eruption from bottom to top, but is usually characterized by the thick intermediate and basic volcanic rocks of cycle 2 (Fig. 2).

3. Volcanic reservoir features

3.1. Lithologic features

Lithology and lithofacies are the basic geologic attributes of volcanic rocks, therefore, they are the basic content in volcanic reservoir depiction and the study on reservoir development rules. Based on 77 m observed cores taken from the volcanic interval of the Changling fault depression and 663 slices analyzed under microscope, lithology and lithofacies identification as well as sequence division were conducted on the 19,384 m volcanic interval of fault depression stage encountered in 66 wells, and statistics were conducted on its development rules.

The deep volcanic rocks in the Songliao Basin can be divided into volcanic lava, volcaniclastic lava, volcaniclastic rocks and sedimentary volcaniclastic rocks based on rock texture – origin, and then, the specific rock types can be identified based on mineral component, characteristic structure and pyroclast size grade and ratio [3]. A total of 30 types of volcanic rocks were developed in the Changling fault depression, among which, 11 types were mostly developed and relatively closely related to the reservoirs, as is shown in Fig. 3.

3.1.1. Volcanic lava category

Rhyolite presents a porphyritic structure, with a few phenocryst mainly consisting of quartz and alkali feldspar, frequently with rhyolitic structure (Fig. 4a and b); dacite presents a porphyritic structure, with phenocryst being dominated by quartz and plagioclase, rare basic feldspathic phenocryst, with more plagioclase phenocryst being different from rhyolite and the occurrence of quartz phenocryst being different from andesite, and matrix mostly of felsitic texture (Fig. 4c and d); trachyte presents more porphyritic structures, and is mainly characterized by the universal occurrence of basic feldspathic phenocryst (Fig. 4e and f); andesite presents more porphyritic structures, with phenocryst being dominated by plagioclase, followed by pyroxene (Fig. 4g and h); and basalt presents a porphyritic structure, with phenocryst being dominated by plagioclase, pyroxene and olivine, and matrix being dominated by intergranular texture (Fig. 4i and j).

3.1.2. Volcaniclastic lava category

Both rhyolitic breccia lava (Fig. 4k) and rhyolitic tuffaceous lava (Fig. 4l and m) are the rocks resulted from the compacting consolidation of magma cemented rhyolitic pyroclastics, which are subdivided into breccia lava (clastic size ranges 2–64 mm) and tuffaceous lava (clastic size less than 2 mm) based on the size of pyroclastics, and all are the transitional rocks between volcanic lava and volcaniclastic rock, in which flow structure (false rhyolitic structure) is often seen.

3.1.3. Volcaniclastic rock category

A volcaniclastic rock is a rock resulted from the compaction and consolidation of volcaniclastic accumulations, and is often with a packing structure. Both rhyolitic volcanic breccia

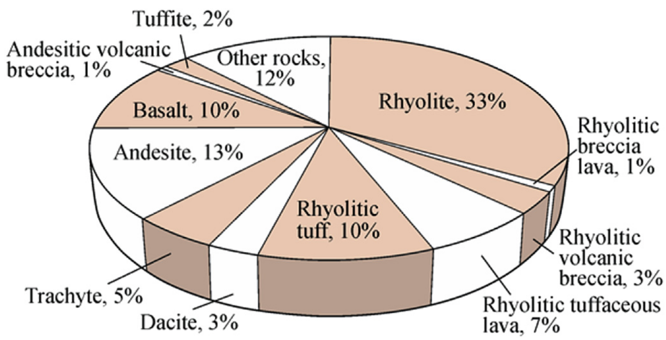

Fig. 3. Volcanic rock types and their thickness percentages of the Changling fault depression. Note: Based on statistics of 19,384 m volcanic interval encountered in 66 wells, other lithology includes dacitic tuff, andesitic tuff, trachyandesitic tuff, trachyandesite, basaltic volcanic breccia, dacite volcanic breccia, dacitic tuffaceous lava, basaltic tuff, trachytic volcanic breccia, sedimentary volcanic breccia, trachytic tuff, trachytic volcanic breccia, trachytic tuffaceous lava, trachytic breccia lava, andesitic basalt, dacitic breccia lava, andesitic tuffaceous lava, perlite and andesitic breccia lava (19 types in total), however, due to their small percentages and poor physical properties, merged statistics were conducted on them for highlighting the regularity of reservoirs.

(Fig. 4n) and rhyolitic tuff (Fig. 4o and p) are the rocks resulted from compaction and consolidation of rhyolitic pyroclastics, which are divided into breccia and tuff based on their sizes (the same size grading as above).

Andesitic volcanic breccia (Fig. 4q) is formed by the compaction and consolidation of andesitic volcaniclastic accumulations.

3.1.4. Sedimentary volcaniclastic rock category

Tuffite (Fig. 4r) is a rock type between volcaniclastic rock and sedimentary rock; affected by volcanism and sedimentary transformation, its diagnostic feature is whether it contains other terrigenous clastics.

3.2. Lithofacies features

In this paper, the division program of "lithology-fabric-origin" five facies and fifteen subfacies [5] was adopted. Four facies and eleven subfacies volcanic rocks are mainly developed in the Changling fault depression, among which, lower and middle subfacies of effusive facies as well as hot clastic flow subfacies of explosive facies predominate, and they totally account for 63.7% of the total lithofacies thickness. The distribution characteristics of each volcanic facies and subfacies as well as its relationship with volcanic edifice – facies belts are listed in Table 1.

3.3. Reservoir physical properties

Based on integrated interpretation results of well test, well logging and mud logging, the volcanic reservoir was divided into gas zone, water layer, poor gas zone and dry layer, and simultaneously, statistical analysis was conducted on the physical property data (porosity–permeability) of 450 volcanic rock samples. The results (Fig. 5) show that the samples with well test result showing gas zone all have a porosity value higher than 3%, but its permeability distribution scope is large, about 0.01–76.90 mD, without apparent cutoff. Porosity and permeability correlation analysis was conducted on all samples, and a correlation coefficient $r = 0.62$ was obtained, The samples with porosity higher than 6% were independently analyzed, and a correlation coefficient $r = 0.78$ was obtained. These results show an apparent increase of permeability with the increase of porosity because when the porosity is less than 6%, the permeability changes little with the increase of porosity and some samples even constitute a "platform", within which, the porosity and permeability correlation is poor, and thus it has an effect on the correlation of the whole porosity and permeability. It is believed based on the above features that both porosity and permeability values have a marked effect on the hydrocarbon accumulation of volcanic reservoirs, moreover, porosity has an apparent hydrocarbon accumulation cutoff, and thus has a greater effect on hydrocarbon accumulation than permeability.

Based on the physical properties of all types of reservoirs mentioned above, combined with experiences in the exploration and development of volcanic rocks in the Songliao Basin summed up by the previous researchers [20], with 3%/6% as the node of porosity classification division and 0.1 mD/1 mD as the node of permeability classification division, the porosity and permeability of volcanic reservoirs in the Changling fault depression were classified into low porosity (less than 3%), middle porosity (3%–6%), high porosity (higher than 6%), low permeability (less than 0.1 mD), middle permeability (0.1–1.0 mD) and high permeability (higher than 1 mD). By this classification, the volcanic samples with porosity higher than 3% account for 71.3% of the total samples in the area, showing a middle–high porosity reservoir; samples with permeability between 0.01 mD and 1.00 mD account for 87.6% of the total, showing a middle–low permeability reservoir.

4. Effective reservoir distribution rules

An effective volcanic reservoir refers to the one that can accumulate and seep fluid (gas and water) and from which commercial fluid rate can be produced under the existing technological and economic conditions [21]. The effective reservoir in this paper includes a gas zone, a poor gas zone and a water layer with a volcanic rock as the host rock. The physical properties of the volcanic rock are an important factor affecting the potential of its becoming an effective reservoir.

4.1. Relationship between effective reservoir distribution and volcanic eruption cycles

Volcanic rock is usually formed by multiphasic volcanic eruptions; whereas the asynchronous volcanic rocks have complex contact relationships and obviously different features, and the reservoir properties and effective reservoir distribution status are also different to some extent. Based on the measured physical property data, integrated hydrocarbon interpretation

Fig. 4. Representative cores and corresponding SEM photos of major volcanic rocks of the Changling fault depression. Note: a. rhyolite, Well YS 2, 3765.2 m deep, lower subfacies of effusive facies; b. SEM photo of core in Fig. 4a (Q represents quartz), single polar, 4 × 10; c. dacite, Well DB 11, 3755.4 m deep, upper subfacies of effusive facies; d. SEM photo of core in Fig. 4c, crossed polars, 4 × 10; e. trachyte, Well XS1, 3530.5 m deep, lower subfacies of effusive facies; f. SEM photo of core in Fig. 4e (Or represents orthoclase), crossed polars, 2 × 10; g. andesite, Well SN 180, 2714 m deep, lower subfacies of effusive facies; h. SEM photo of core in Fig. 4g (Pl represents plagioclase, Px represents pyroxene), crossed polars, 4 × 10; i. basalt, Well DB 10, 2565.87 m deep, upper subfacies of effusive facies; j. SEM photo of core in Fig. 4i; k. rhyolitic breccia lava, Well YS 2, 3764.38 m deep, volcanic neck subfacies of volcanic conduit facies; l. rhyolitic tuffaceous lava, Well YS 102, 3726.54 m deep, hot clastic flow subfacies of explosive facies; m. SEM photo of core in Fig. 4l, single polar, 2 × 10; n. rhyolitic volcanic breccia, Well YS 301, 3860.04 m deep, hot clastic flow subfacies of explosive facies; o. rhyolitic breccia-bearing tuff, Well YS 5, 4374.5 m deep, hot clastic flow subfacies of explosive facies; p. SEM photo of core in Fig. 4o, single polar, 2 × 10; q. andesitic volcanic breccia, Well SN 180, 2638.9 m deep, fallout subfacies of explosive facies; r. tuffite, Well YS 301, 3857.84 m deep, rehandling volcanic sedimentary rock subfacies of volcanic sedimentary facies.

Table 1
Lithofacies types and their percentages of volcanic rocks in the Changling fault depression.

Facies	Subfacies	Thickness percentage	Volcanic edifice – facies belts
Volcanic sedimentary facies V	Tuff and coal interbed sedimentary subfacies V_3	/	Marginal facies belt, low-lying zone between volcanic edifices
	Rehandling pyroclastic sedimentary rock subfacies V_2	1.1%	
	Extraclast-bearing volcanic sedimentary rock subfacies V_1	1.7%	
Extrusive facies IV	Outer-zone subfacies IV_3	/	Crater – near-crater facies belt
	Mesozone subfacies IV_2	/	
	Intrazone subfacies IV_1	/	
Effusive facies III	Upper subfacies III_3	14.0%	Crater – near-crater facies belt, proximal facies belts
	Middle subfacies III_2	17.2%	
	Lower subfacies III_1	31.6%	
Explosive facies II	Hot clastic flow subfacies II_3	14.9%	Crater – near-crater facies belts, proximal facies belts, distal facies belts
	Hot base surge subfacies II_2	7.3%	
	Fallout subfacies II_1	6.9%	
Volcanic conduit facies I	Cryptoexplosive breccia subfacies I_3	1.3%	Crater – near-crater facies belt
	Subvolcanic rock subfacies I_2	1.7%	
	Volcanic neck subfacies I_1	2.3%	

Note: Based on 19,384 m volcanic well intervals (66 wells).

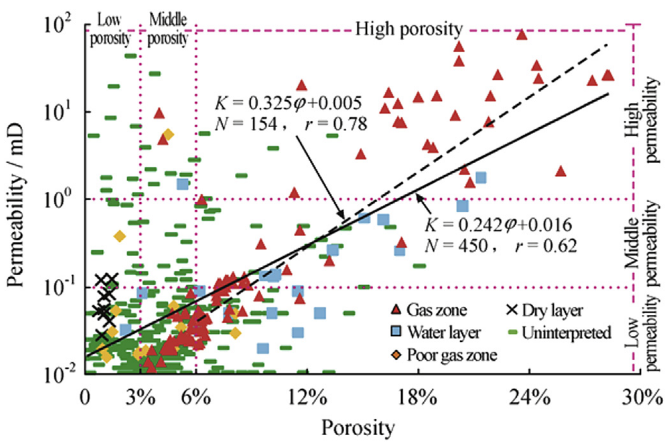

Fig. 5. Porosity vs permeability of volcanic rocks in the Changling fault depression. Note: Based on 450 sets of measured physical property (porosity–permeability) data, both gas zone and dry layer are well test results, and poor gas zone and water layer are integrated well logging and mud logging interpretation results.

results and well test data, statistical analysis was conducted on the reservoir property and effective reservoir distribution of the volcanic eruption cycles of Members III and I of the Yingcheng Formation and Member II of the Huoshiling Formation. The analysis results show that most samples taken from cycles 3 and 2 of Member III, Yingcheng Formation, as well as from cycle 3 of Member I, Yingcheng Formation, have high–middle porosities and permeabilities, indicating a good physical property condition on the whole (Fig. 6a). With the percentage and thickness of effective reservoirs taken into consideration, it is believed that the effective reservoir proportion is high and the effective reservoir development thickness is large in cycle 3 of Member III, and cycle 3 of Member I, Yingcheng Formation; the effective reservoir proportion is high in cycle 5 of Member II, Huoshiling Formation, whereas the effective reservoir thickness is large in cycle 1 (Fig. 6b).

The classified evaluation on volcanic reservoir eruption cycle/lithology/lithofacies were mainly conducted based on the reservoir property and productivity (comprehensively evaluating the effective reservoir thickness and percentage based on integrated well logging and mud logging interpretation results and productivity data). It is believed that class I eruption cycle/lithology/lithofacies exhibits good physical property and high productivity, good physical property and moderate productivity, and moderate physical property and high productivity; class II eruption cycle/lithology/lithofacies exhibits poor physical property and high productivity, moderate physical property and moderate productivity; whereas class III eruption cycle/lithology/lithofacies exhibits good physical property and low productivity, moderate physical property and low productivity, poor physical property and moderate productivity, and poor physical property and low productivity.

Based on the above analysis, there is an excellent corresponding relationship between the reservoir property and the effective reservoir development level of each cycle, moreover, the top cycle of each volcanic interval has higher effective reservoir proportion and larger thickness, and is the predominant cycle for the formation of effective reservoirs.

4.2. Relationship between effective reservoir distribution and lithology

Because volcanic rocks are strongly heterogeneous, those with different lithologies have different attributes such as density, composition, texture and structure, resulting in their different physical properties. Based on the measured physical property data, integrated hydrocarbon interpretation results and well test data, statistical analysis was conducted on the reservoir property and effective reservoir distribution of the 11 volcanic rocks mainly developed in the Changling fault depression. The analysis results show that the lithology with good physical property conditions includes rhyolite, andesitic

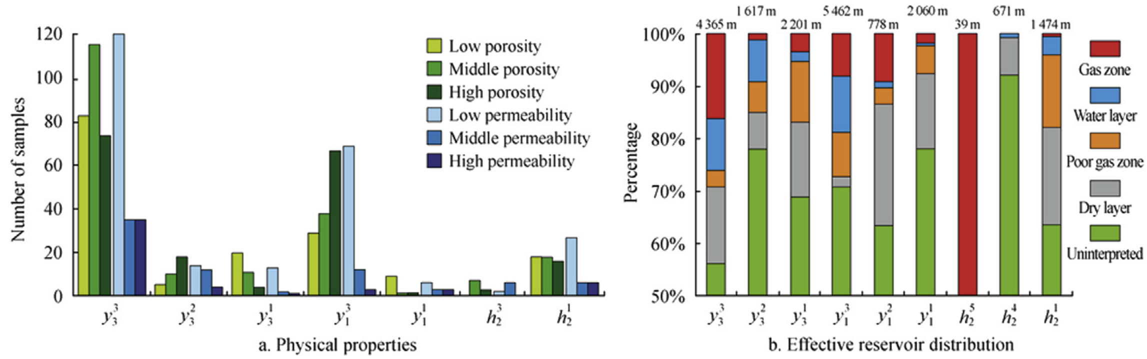

Fig. 6. Relationship between volcanic reservoir properties, effective reservoir distribution and cycles. Note: The code of each cycle corresponds to Fig. 2 and is simplified, e.g., y_3^3 represents cycle 3 of Member III, Yingcheng Formation. a: porosity and permeability classification principle is the same as that in the above paragraphs; there are a total of 546 measured porosity data points and 450 measured permeability data points respectively, however, cycle 2 of Member I, Yingcheng Formation and cycles 5 and 4 of Member II, Huoshiling Formation are short of porosity and permeability data. b: The numerals above the histogram are the development thickness of each cycle respectively, with unit of m; although 341 m volcanic reservoir is developed in cycle 3 of Member II, Huoshiling Formation, it is not counted due to the absence of integrated interpretation. The effective reservoir thickness and percentage of each cycle are as follows respectively: y_3^3: 1261 m, 21.6%; y_2^3: 326 m, 15.2%; y_1^3: 370 m, 16.9%; y_3^1: 1497 m, 27.4%; y_2^1: 106 m, 13.6%; y_1^1: 158 m, 7.7%; h_5^2: 19 m, 48.7%; h_4^2: 6 m, 0.9%; h_1^2: 259 m, 17.6%.

volcanic breccia, followed by basalt, andesite, tuffite, rhyolitic tuffaceous lava, rhyolitic volcanic breccia, rhyolitic tuff and rhyolitic breccia lava, whereas that with poor physical property conditions is dacite and trachyte (Fig. 7a). Based on an integrated analysis on effective reservoir proportion and development thickness, effective reservoirs are mainly distributed in rhyolite, rhyolitic tuffaceous lava, rhyolitic tuff and rhyolitic volcanic breccia, followed by rhyolitic breccia lava, trachyte, andesite, andesitic volcanic breccia and basalt, and rarely in tuffite and dacite (Fig. 7b).

Based on the above analysis, the lithology of volcanic reservoirs in the area is divided into three types: ① rhyolite, rhyolitic tuffaceous lava, andesitic volcanic breccia, rhyolitic tuff and rhyolitic volcanic breccia are favorable reservoir rocks; ② followed by andesite, basalt and rhyolitic breccia lava; and ③ it is relatively hard for tuffite, trachyte and dacite to form effective reservoirs.

4.3. Relationship between effective reservoir distribution and lithofacies

The physical properties of different volcanic facies are quite different. Based on the measured physical property data, integrated hydrocarbon interpretation results and well test data, statistical analysis was conducted on the reservoir property and effective reservoir distribution of the volcanic facies developed in the Changling fault depression. The analysis results show that the lithofacies with good physical properties include upper subfacies (III_3), middle subfacies (III_2) and volcanic neck subfacies (I_1), followed by hot clastic flow subfacies (II_3), fallout subfacies (II_1) and extraclast-bearing pyroclastic sedimentary rock subfacies (V_1); that with poor physical properties include lower subfacies (III_1), hot base surge subfacies (II_2) and cryptoexplosive breccia subfacies (I_3) (Fig. 8a); the effective reservoir is mainly distributed in hot clastic flow subfacies, upper subfacies and lower subfacies, followed by middle subfacies, fallout subfacies, hot base surge subfacies, cryptoexplosive breccia subfacies and extraclast-bearing volcanic sedimentary rock subfacies, and rarely in volcanic neck subfacies (Fig. 8b).

Based on the above analysis, the lithofacies of the area is divided into three types: ① upper subfacies, hot clastic flow subfacies and middle subfacies are the predominant lithofacies for forming effective reservoirs; ② followed by lower subfacies and fallout subfacies; and ③ It is hard for hot base surge subfacies, volcanic neck subfacies, extraclast-bearing volcanic sedimentary rock subfacies and cryptoexplosive breccia subfacies to become effective reservoirs.

5. Conclusions

1) Effective reservoir and eruption cycle. A total of 10 volcanic eruption cycles are developed in three Members of the Changling fault depression, and the reservoir property and effective reservoir distribution have a good corresponding relationship in these volcanic eruption cycles, among which, the top cycles (cycle 3) of the Yingcheng Formation Member III and Member I have good reservoir properties, high effective reservoir proportion and large thickness, and are the predominant cycles for the formation of effective reservoirs.
2) Effective reservoirs and lithology. A total of 30 volcanic rocks are developed in the Changling fault depression, and 11 of them have relatively good reservoir conditions; the corresponding relationship of reservoir property and effective reservoir is unobvious in these volcanic rocks, and it is believed based on an integrated analysis that rhyolite, rhyolitic tuffaceous lava, andesitic volcanic breccia, rhyolitic tuff and rhyolitic volcanic breccia are the favorable reservoir rocks of the area.
3) Effective reservoirs and lithofacies. A total of 4 volcanic facies and 11 volcanic subfacies are developed in the Changling fault depression, and there is a good

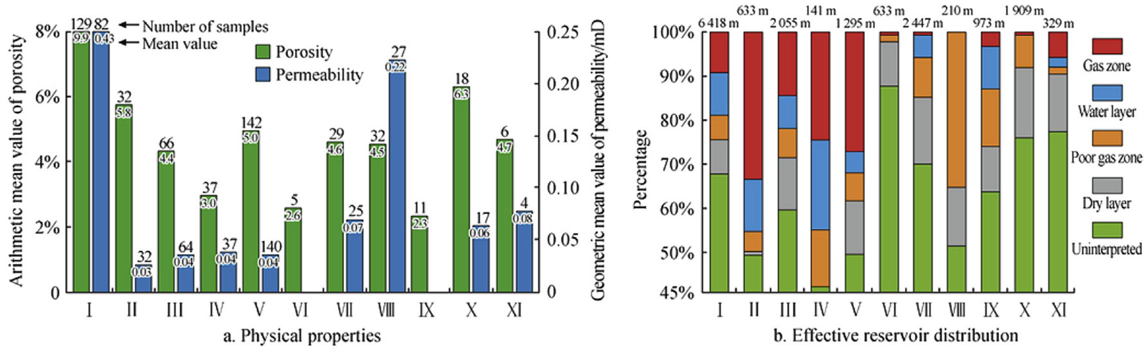

Fig. 7. Relationship between volcanic reservoir properties, effective reservoir distribution and rock types. Note: I – rhyolite; II – rhyolitic volcanic breccia; III – rhyolitic tuff; IV – rhyolitic breccia lava; V – rhyolitic tuffaceous lava; VI – dacite; VII – andesite; VIII – andesitic volcanic breccia; IX – trachyte; X – basalt; XI – tuffite. a: The numeral above the histogram is the number of statistical samples, and that in it is the arithmetic mean value of porosity and geometric mean value of permeability of each lithology; because VI – dacite and IX – trachyte do not have permeability values, they are not counted. b: The numeral above the histogram is the development thickness of each lithology, in unit of m, and the effective reservoir thickness and percentage of each lithology are as follows respectively: I: 1461 m, 22.8%; II: 293 m, 46.3%; III: 543 m, 26.4%; IV: 76 m, 53.9%; V: 460 m, 35.5%; VI: 13 m, 2.0%; VII: 333 m, 13.6%; VIII: 69 m, 32.9 m; IX: 232 m, 23.8%; X: 141 m, 7.4%; XI: 29 m, 8.8%.

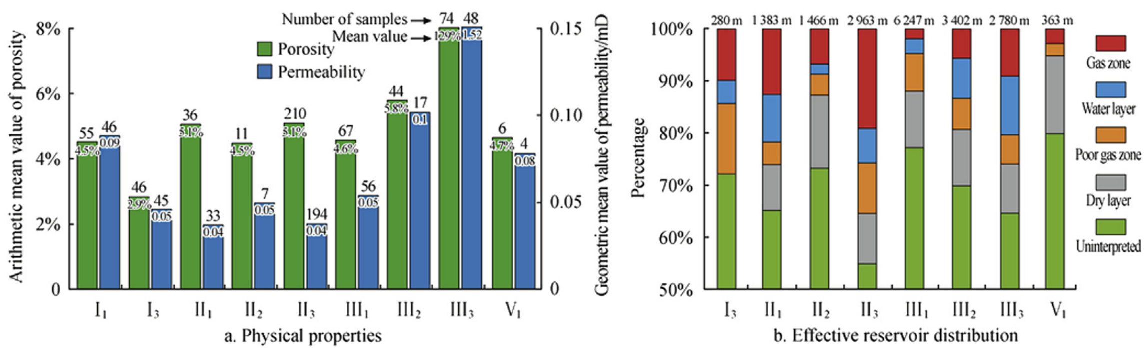

Fig. 8. Relationship between volcanic reservoir physical properties, effective reservoir distribution and lithofacies types. Note: The subfacies code is the same as that in Table 1. a: The numeral above the histogram is the number of samples, and that in it is the arithmetic mean value of porosity and geometric mean value of permeability of each lithofacies. b: The numeral above the histogram is the development thickness of each lithofacies, in unit of m; because I_1 (volcanic neck subfacies) is not interpreted, it is not counted, whereas the effective reservoir thickness and percentage of other subfacies are as follows respectively: I_3: 66 m, 23.6%; II_1: 358 m, 25.9%; II_2: 187 m, 128%; II_3: 1050 m, 35.4%; III_1: 755 m, 12.1%; III_2: 661 m, 19.4%; III_3: 723 m, 26.0%; V_1: 19 m, 5.2%.

corresponding relationship between reservoir property and effective reservoir distribution in them; the upper subfacies, hot clastic flow subfacies and middle subfacies have good reservoir properties, high effective reservoir proportion and large thickness, and are the predominant lithofacies for the formation of effective reservoirs.

4) Effective reservoirs and porosity and permeability. The quality of volcanic reservoir property has a good corresponding relationship with the development level of an effective reservoir, and the effect of porosity on the formation of an effective reservoir is greater than permeability; as a whole, the volcanic rocks in the Changling fault depression are high-middle porosity and middle-low permeability reservoirs, with better porosity conditions, which shows that the exploration of deep volcanic rocks has a good prospect.
5) Exploration direction of effective volcanic reservoirs. Based on the development rules of effective reservoirs, the exploration in the area should firstly focus on the rhyolitic composite volcanic edifice to highlight the depiction of large weathered crust type volcanic sequence boundary in the blister-like cone and its vicinity, with the top cycles of the Yingcheng Formation Member I and Member III should be as the important exploration target intervals.

References

[1] Feng Zhiqiang, Liu Jiaqi, Wang Pujun, Chen Shumin, Feng Zihui, Tong Ying. New oil and gas exploration field: volcanic hydrocarbon reservoirs – enlightenment from the discovery of the large gas field in Songliao Basin. Chin J Geophys 2011;54(2):269–79.

[2] Zou Caineng, Zhao Wenzhi, Jia Chengzao, Zhu Rukai, Zhang Guangya, Zhao Xia, et al. Formation and distribution of volcanic hydrocarbon reservoirs in sedimentary basins of China. Pet Explor Dev 2008;35(3):257–71.

[3] Sun Longde, Zou Caineng, Zhu Rukai, Zhang Yunhui, Zhang Shuichang, Zhang Baomin, et al. Formation, distribution and potential of deep hydrocarbon resources in China. Pet Explor Dev 2013;40(6):641–9.

[4] Wang Pujun, Zheng Changqing, Shu Ping, Liu Wanzhu, Huang Yulong, Tang Huafeng, et al. Classification of deep volcanic rocks in Songliao Basin. Pet Geol Oilfield Dev Daqing 2007;26(4):17–22.

[5] Wang Pujun, Chi Yuanlin, Liu Wanzhu, Cheng Rihui, Shan Xuanlong, Ren Yanguang. Volcanic facies of the Songliao Basin: classification, characteristics and reservoir significance. J Jilin Univ Earth Sci Ed 2003;33(4):449−56.

[6] Shu Ping, Ding Rixin, Qu Yanming, Ji Xueyan. Lithologic and lithofacies patterns of volcanic reservoirs in Xushen Gas Field. Nat Gas Ind 2007;27(8):23−8.

[7] Gao Youfeng, Wu Yanhui, Liu Wanzhu, Qu Xuejiao, Tang Huafeng. Intercrystaline micropore characteristics and reservoir effect of Yingcheng Formation volcanic rock in Yingtai fault depression, southern Songliao Basin. Acta Pet Sin 2013;34(4):667−74.

[8] Wu Yanxiong, Wang Pujun, Wu Yanhui, Yan Lin, Yang Di. Components of volcanic reservoir space: a case study from the Songliao Basin. Nat Gas Ind 2011;31(4):28−33.

[9] Luo Jinglan, Shao Hongmei, Yang Yanfang, Li Miao, Luo Chunyan. Temporal and spatial evolution of burial − hydrocarbon filing − diagenetic process of deep volcanic reservoir in Songliao Basin. Earth Sci Front 2013;20(5):175−87.

[10] Feng Zihui, Shao Hongmei, Tong Ying. Controlling factors of volcanic gas reservoir property in Qingshen Gas Field, Songliao Basin. Acta Geol Sin 2008;82(6):760−9.

[11] Hou Qijun. Main controlling factors of volcanic reservoirs in the southern Songliao Basin. Acta Pet Sin 2011;32(5):749−56.

[12] Cai Dongmei, Sun Lidong, Qi Jingshun, Dong Jinghai, Zhu Yingkang. Reservoir characteristics and evolution of volcanic rocks in Xujiaweizi fault depression. Acta Pet Sin 2010;31(3):400−7.

[13] Qu Xuejiao, Wang Pujun, Yao Ruishi, Gao Youfeng, Bai Bing. Stratigraphical sequence and regional correlation of Huoshiling Formation in the southern of Songliao Basin. J Central South Univ Sci Technol 2014;54(8):2716−27.

[14] Xiao Yongjun, Xu Youde, Duan Xiaoyan, Yu Yongli. Huoshiling hydrocarbon accumulation in Dongling area of Changling depression. Nat Gas Geosci 2012;23(4):720−6.

[15] Chen Xiaoguang. Jilin yearbook 2010. Changchun: Jilin Annual Press; 2010.

[16] Zhu Youhong, Wang Jun. Resource potential in the deep of the Shiwu fault depression and the Changling sag, Songliao Basin. Pet Geol Exp 2003;25(2):149−52.

[17] Wang Pujun, Zhao Ranlei, Meng Qi'an, Qu Xuejiao, Zhu Defeng, Gao Youfeng. The Cretaceous Songliao Basin: dynamic background from volcanic rift to interior sag basin. Earth Sci Front 2015;22(3):72−91.

[18] Huang Yulong, Wang Pujun, Men Guangtian, Tang Huafeng. Division of volcanic cycles and stages of the Yingcheng Formation of the Songliao Basin: take the cross sections at the margin and the boring holes as examples. J Jilin Univ Earth Sci Ed 2007;37(6):1183−91.

[19] Jia Juntao, Wang Pujun, Shao Rui, Cheng Ri hui, Zhang Bin, Hou Jingtao, et al. Stratigraphical sequence and regional correlation of Yingcheng Formation in the southeast of Songliao Basin. J Jilin Univ Earth Sci Ed 2007;37(6):1110−23.

[20] Xu Zhengshun, Wang Yuming, Pang Yanming, Ai Xingbo. Development of volcanic rock reservoirs in the Xushen Gas Field in Daqing. Nat Gas Ind 2008;28(12):74−7.

[21] Guo Rui. Supplement to determining method of cut-off value of net pay. Pet Explor Dev 2004;31(5):140−4.