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 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
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 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.
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 compacting 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, andesitic 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, dacite breccia lava, andesitic tuffaceous lava, andesitic volcanic breccia. 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. 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. 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. 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.
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 XS 1, 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, Ppx 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.
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

| 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 V₃ | /                         | Marginal facies belt, low-lying zone between volcanic edifices |
|                                   | Rehandling pyroclastic sedimentary rock subfacies V₂ | 1.1%                     |                          |
|                                   | Extraclast-bearing volcanic sedimentary rock subfacies V₁ | 1.7%                     |                          |
| Extrusive facies IV               | Outer-zone subfacies IV₃         | /                         | Crater — near-crater facies belt |
|                                   | Mesozone subfacies IV₂           | /                         |                          |
|                                   | Intrazone subfacies IV₁          | /                         |                          |
| Effusive facies III               | Upper subfacies III₃             | 14.0%                     | Crater — near-crater facies belt, proximal facies belts |
|                                   | Middle subfacies III₂            | 17.2%                     |                          |
|                                   | Lower subfacies III₁             | 31.6%                     |                          |
| Explosive facies II               | Hot clastic flow subfacies II₃   | 14.9%                     | Crater — near-crater facies belt, proximal facies belts |
|                                   | Hot base surge subfacies II₂     | 7.3%                      |                          |
|                                   | Fallout subfacies II₁            | 6.9%                      |                          |
| Volcanic conduit facies I         | Cryptovolcanic breccia subfacies I₃ | 1.3%                     | Crater — near-crater facies belt |
|                                   | Subvolcanic rock subfacies I₂    | 1.7%                      |                          |
|                                   | Volcanic neck subfacies I₁       | 2.3%                      |                          |

Note: Based on 19,384 m volcanic well intervals (66 wells).
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, rhyolitic 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 (III₃), middle subfacies (III₂) and volcanic neck subfacies (I₁), followed by hot clastic flow subfacies (II₃), fallout subfacies (I₂) and extraclast-bearing pyroclastic sedimentary rock subfacies (V₁); that with poor physical properties include lower subfacies (III₁), hot base surge subfacies (II₂) and cryptoexplosive breccia subfacies (I₃) (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, andesite and eruptive 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...
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 Changle 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


