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Reservoir characteristics in the Cretaceous volcanic rocks of Songliao Basin, China: A case of dynamics and evolution of the volcano-porosity and diagenesis

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Abstract

To explain the strong spatial heterogeneity of volcanic reservoirs porosity in the Songliao Basin and provide new ideas for predicting good volcanic reservoirs in other similar basins, the relationship between the pore evolution process and lithology of volcanic reservoirs has been described in this article. With the description and interpretation of core, thin section, scanning electron microscope, and the results of mercury injection experiment, this article clarifies the lithology, pore types, and pore structure features of the volcanic reservoirs in the Songliao Basin. The rocks of volcanic reservoirs in study area contain pyroclastic rock and volcanic lavas. The most common lithologies are rhyolite, volcanic breccia, and volcanic tuff. The pore size, morphology, and structure vary greatly between these three lithologies, the reason of which we think is the different volcanic eruption process as well as rock composition and its structure. The digenetic evolution of rhyolite includes gas dissipation of magmatic condensation; vesicles fulfilling by hydrothermal fluid; kaolinization and sericitization of feldspar phenocrysts; carbonation, devitrification, and recrystallization of felsic matrix; and finally, the dissolution of feldspar phenocrysts and felsic matrix. As for volcanic breccia, it usually go through the compaction, quartz and calcite filling the original pores between volcanic breccias, and dissolution of mineral debris together with tuff matrix. Similar with the rhyolite, volcanic tuff also undergoes the carbonation and kaolinization of felsic matrix, the dissolution of feldspar and felsic matrix, and compaction.

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Due to these comprehensive processes, a comprehensive analysis of volcanic rock lithology, which can indicate lithology distribution vertically and horizontally, is very necessary during volcanic reservoirs evaluation and prediction. These detailed analyses will help explorers to find potential reservoirs by distinguishing the diagenetic evolution and pore characteristic of volcanic reservoirs.

Keywords
Diagenesis, pore structure, lower Cretaceous, volcanic rock, Songliao Basin

Introduction

The first volcanic gas reservoir was found in the San Joaquim Basin in Northern California in the United States in 1887 (Gries et al., 1997; Liu, Meng, et al. 2010). Since then, hydrocarbon reservoirs have been found in volcanic rocks on five continents around the world (Lenhardt and Götz, 2011; Magara, 2003; Schutter, 2003; Sruoga and Rubinstein, 2007). In China, after the discovery of the first volcanic gas reservoir in well XS1 in 2002, volcanic rocks have been a favorable target for natural gas exploration as an unconventional gas resource in Yingcheng Formation of the Cretaceous in Songliao Basin (Feng, 2008; Yang et al., 2006). Successions of volcanic rocks are widely deposited in Songliao Basin from 1700 to 6200 m, and volcanic reservoirs were found mostly below 3000 m. The Songliao Basin is the most productive oil and gas field in China, but recent studies have demonstrated that the volcanic reservoirs may increase the proven reserves up to 1000×10^8 m^3 (Feng et al., 2010). Due to the increased interest in the volcanic rocks, their reservoir characteristics have been detailed studied in the past (Chen, 2002; Wu et al., 2006; Zou et al., 2008). Only simple conclusions were proposed to explain their reservoir development, namely, that they were linked to tectonic fracturing or the rock dissolution (Dai et al., 2007; Du et al., 2012; Guo et al., 1997; Luo et al., 2008; Liu et al., 2010; Meng et al., 2002; Zhao, 1996). Since 2003, China National Petroleum Corporation has conducted several studies in the Songliao Basin to constrain the reservoir evolution and its controls. That had led to the conclusion of two different porosity of volcanic reservoir in the Songliao Basin: (1) primary porosity controlled by volcanic processes and (2) secondary porosity controlled by disillusion and tectonic fracturing (Huang et al., 2010; Liu, 2004; Liu et al., 2008; Wang et al., 2006; Witte et al., 2012; Yang et al., 2007; Zhang et al., 2007). However, the reservoir quality prediction is still an unsolved problem for the high risk of volcanic reservoir exploration in the Songliao Basin (Chen et al., 2011; Sun and Zhong, 2017; Wang and Chen, 2015).

So, the objective of this article is not to make a comprehensive review of volcanic reservoirs but to (1) characterize and explain the porosity of different volcanic rocks and (2) analyze the controlling factors for the reservoir quality of volcanic rocks, including but not limited to the volcanic processes and diagenesis of different volcanic rocks. This study was carried out by integrating the lithology, diagenesis, and eruption processes with the physical property. The most important part of this study is the interpretation of the primary and secondary porosity of different volcanic rocks, which are dependent both on the lithology and on the sequence of eruption processes (Gaonac et al., 2005; Rohrman, 2007). Therefore, the appropriate model of volcanic facies is required to constrain the influence on their lithology distribution in the volcanic edifice (Tang et al., 2007; Watton et al., 2013). The pyroclastic rocks and lavas are both included in the volcanic reservoirs of the Songliao Basin, so the processes of magma cooling, solidification, and alteration including weathering and tectonic fracturing since the eruption are all in the scope of this article. The results of this work will provide implications for further exploration of the volcanic reservoirs in the Songliao Basin, and possibly, for volcanic plays elsewhere.

Geological background

The Songliao Basin is a giant terrestrial basin, with a length of 750 km and a width of 350 km, filled with Jurassic and Cretaceous volcanic rocks and sedimentary rocks (Figure 1). The basement of the basin comprises metamorphic rocks and igneous rocks from Paleozoic and Precambrian. From the Late Triassic to the early period of Late Jurassic, there were the lithosphere reduction and the Moho uplifting, which were caused by the uplifting and weathering of the earth's crust, and then the differentiated acidic magma bursted along the north north-east fractures (Metelkin et al., 2010; Wu et al., 2005) (Figure 1). Later, from the middle of Late Jurassic to the early stage of Early Cretaceous, crust shrinked due to temperature reduction and the Moho restore (Yang et al., 2004). The top of volcanic dome collapsed, leading the extension structures and formation of the Songliao Basin (Wang et al., 2016). In the western part of the basin, the earth crust was broken intensely, so the magma moved easily along those fractures, where volcanic rocks of Yingcheng Formation we studied were developed during this period in Xujiaweizi Depression, an explored volcanic gas reservoir play (Figure 1; Cheng et al., 2003). In this study area, the lithology of the volcanic rocks includes basalt, andesite, dacite, rhyolite, tuff, and volcanic

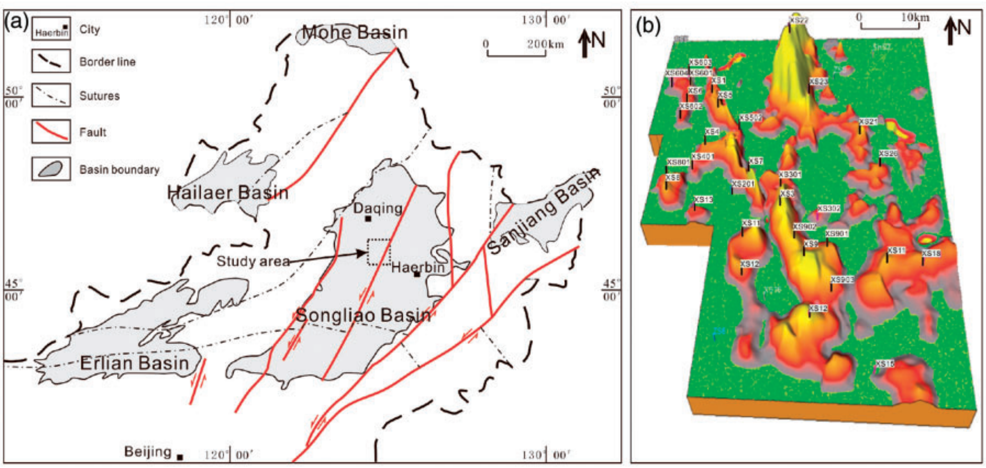

Figure 1. (a) Location of the study area and the structure units of the North China Plate. Our study area is located near the north north-east fractures of Songliao Basin, which is the passway of the deep magmas. (b) Sketch map showing the locations of different wells and volcanic edifice in study area, and some wells are just lying at the ancient volcanic edifice. The three largest ancient volcanic edifice are drilled by well XS22, XS9, and XS12. The location of map (b) is the square area in map (a).

breccia (Wang et al., 2007) (Figure 2). Porosity was changed from 1.9% to 10.8%, while the permeability varied from 0.01×10^{-3} μm^2 to 0.87×10^{-3} μm^2 (Wang et al., 2008).

Data and method

Drill cores and cuttings data used in this article were obtained from the Daqing Oilfield Company. Over 200 rock samples from drill cores and cuttings of the Yingcheng Formation (K1y, Barrenmian, and Aptian) have been studied for lithology and diagenesis using thin section analysis (Figure 2). Porosimeter porosity and permeability of drill cores were analyzed in the laboratory of China University of Petroleum. For counting pores and fracture

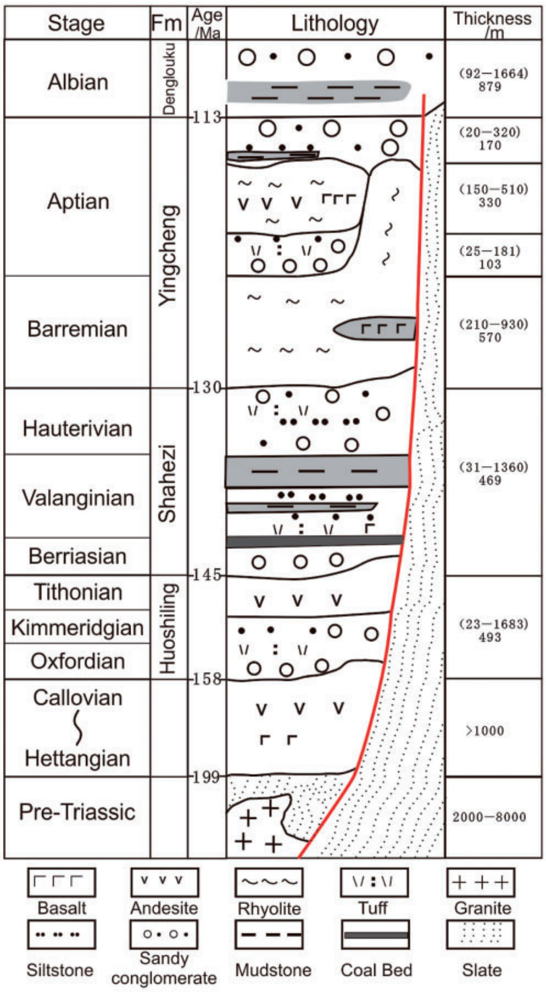

Figure 2. Column showing different lithology with age and thickness of the Jurassic and Cretaceous in Songliao Basin. From the Hettangian to Barremian, the successions of volcanic rocks were developed in the study area with basalt, andesite, rhyolite, and tuff. In the Yingcheng Formation we studied, the lithology of volcanic rocks is mainly rhyolite, tuff, and andesite (Wang et al., 2007).

of the volcanic rocks, image analysis was used to the high-resolution photographs of thin sections impregnated with colorful dye-stained resin. Lithologic definitions are based on Pujun Wang (Wang and Chen, 2015): (1) lava, (2) welded ignimbrite or ignimbrite, (3) pyroclastic rocks, (4) tuff, and (5) tuffite.

Characteristics of petrography and porosity

Petrography characteristics

Based on the detailed observation of the 239 thin section samples and the results of point counting, we find that the lithology of the volcanic reservoirs in study area includes tuff, volcanic breccia, ignimbrite, rhyolite, basalt, and andesite. However, the rhyolite, tuff, and volcanic breccia account for the largest proportion (Figure 3). Rhyolite presents porphyritic structure and rhyolitic structure, and most volcanic glasses have been transformed into felsic phenocrysts through devitrification, such as sanidine, quartz, and acidic plagioclase, but no biotite and hornblende. Rhyolite can be divided into vesicular rhyolite, spherulitic rhyolite, and felsite. Tuff accounts for the largest proportion in study area, which contains little coarse volcanic debris, such as crystal fragments, glass fragments, and a few breccia. The cores of volcanic breccia are dense and solid, with great amount of angular rigid cuttings. The breccia is poorly sorted and disorientated, and its pores are filled by volcanic ash, with quartz, feldspar, and other crystal fragments (Figure 4).

Pore characteristics

The pore types of volcanic reservoirs in the study area include primary pores and secondary pores (Table 1), which are discussed in the following.

Capacity of volcanic reservoir pores is related to pore size closely. According to their pore diameter, they can be divided into large pores (larger than 1 mm), medium pores (0.1 mm–1 mm), small pores (0.01 mm–0.1 mm), and micropores (smaller than 0.1 mm). Based on thin section observation results, the pores of the volcanic reservoirs in study area are mainly small pores (accounting for 40%) followed by medium pores and micropores (medium pores 28% and micropores 22%) and large pores were relatively less (only accounts 10%). Usually, large pores appear inside vesicular rhyolite or volcanic breccia, and medium and small pores are common seen in the ignimbrite, tuff, and rhyolite. As for micropores, they are widespread inside the matrix of crystal tuff and spherulitic rhyolite.

Except pore size, the pore morphology of volcanic reservoirs also varies in study area. Their shapes include elliptical, angular, rectangular, triangular, irregular, dispersive, dendritic, and belted (Figure 5). Pore morphology is closely related to the formation of pores. For example, usually the primary pores are elliptical, and micropores may be in dispersive shape after the matrix dissolution. In turn, it is unlikely for pores to develop into a dendritic shape, and the dissolved pores inside matrix may not become rectangular. Therefore, the proportions of different pore morphology vary due to different volcanic rock types. Usually, elliptical pores are common seen in porous rhyolite, volcanic breccia. The angular pores are often developed in the vesicular rhyolite and rectangular mold pores in the crystal tuff. The triangular pores, mainly mold pores, are common in crystal tuff and vesicular rhyolite. As for irregular pores, they are widespread in crystal tuff and rhyolite. Pores of dispersive morphology are usually developed inside tuff lava, rhyolite, and volcanic breccia, forming

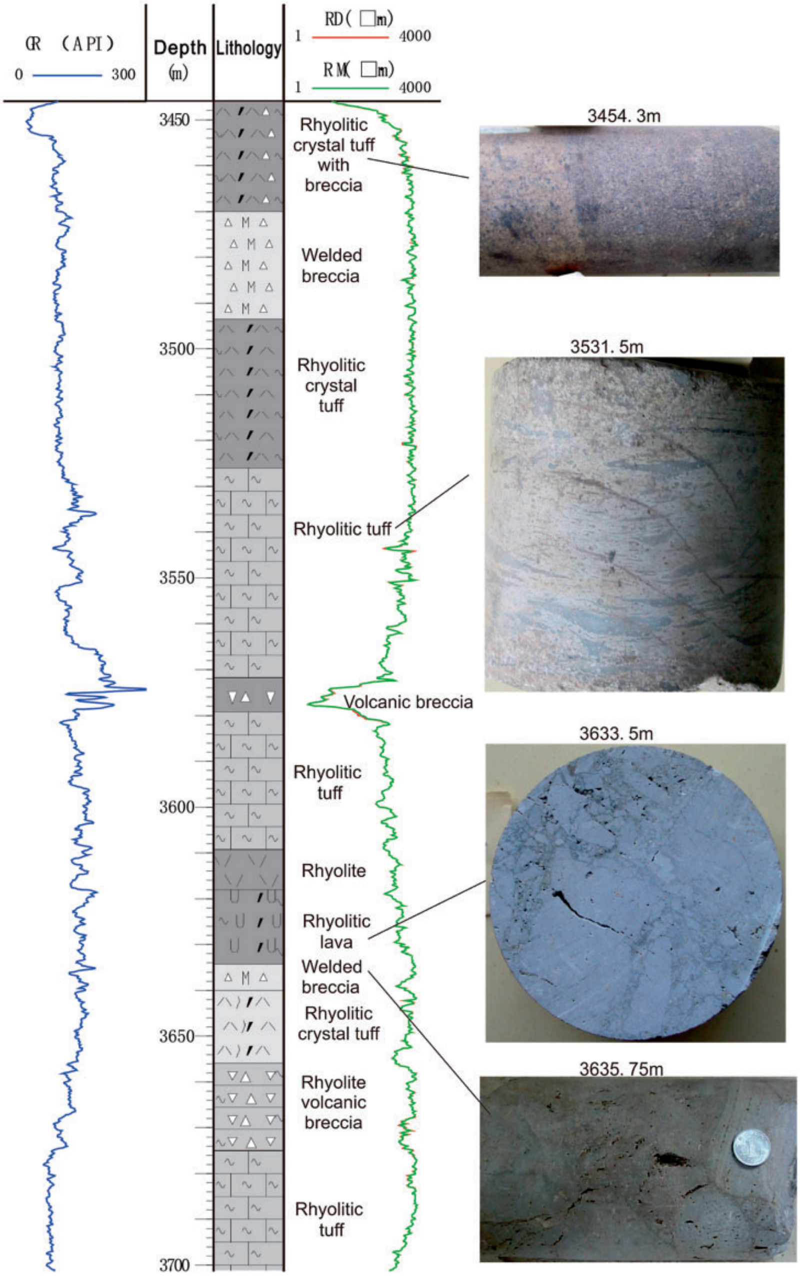

Figure 3. Well column of XS1 showing the lithology change from 3400 m to 3700 m, and some typical core photos are present in the right. The main lithology contains rhyolitic tuff, rhyolitic crystal tuff, rhyolitic crystal tuff with breccia, welded breccia, rhyolite, and rhyolite volcanic breccia.

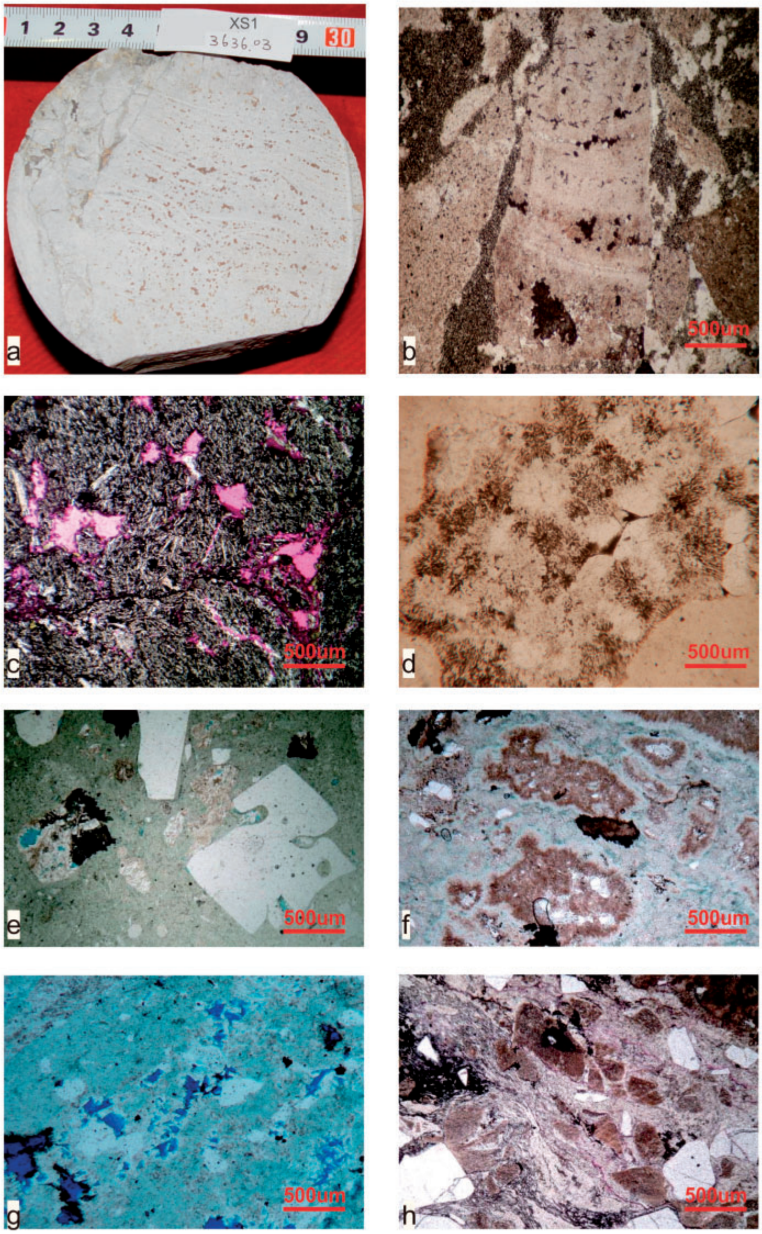

Figure 4. Pictures showing the characteristics of different volcanic rocks in Yingcheng Formation of Songliao Basin. (a) The core of an rhyolite with vesicular structure, well XS1, 3636.03 m; (b) paralleled small vesicular pores in the microscope image of rhyolite, well XS9, 3885 m; (c) tabular feldspars and the dissolution pores in the microscope image of andesite, well CS2, 4055 m; (d) radial spherulite structure in the microscope image of the rhyolite, well XS6, 3852 m; (e) feldspar and quartz phenocryst in the microscope image of tuff, well XS801, 3849.6 m; (f) fake rhyolitic structure in the microscope image of the welded tuff, well XS301, 3907.2 m; (g) dissoluted vesicular structure filled with authigenic quartz in the microscope image of rhyolite, well XS9, 3593.5 m; and (h) small debris in the microscope image of volcanic breccia, well CS 1-3, 3817.5 m.

Table 1. Classification of the pores in volcanic rocks of Yingcheng Formation in the Songliao Basin.

Type	*Subdivision*	*Formation mechanism*	*Characteristics and distribution*
Primary	Vesicles Vesicles in breccia Vesicles in magmatic debris	Exsolution of volatile matters with bubbles aggregated into pores	A clear arc, with a variety of shapes; at the top or bottom of the lava flows, in the breccia and magmatic debris as well as in the matrix
	Inter-breccia pores	Grain supporting Autoclastic brecciation	Remaining space due to piling of rigid breccia with irregularly angular shape
	Intergranular pores	Grain supporting	Cribriform pores are evenly distributed and gradually decreasing or disappearing with the increase of the burial depth
	Intercrystal pores	Crystallization	Polygons, visible under a microscope, in the authigenic minerals and are often filled with volcanic glass, granular dark minerals, or their alteration; in the middle of the intermediate–basic lava flow
Secondary	Intergranular dissolution	Dissolution, hydrolysis, replacement	Volume change because mineral crystals (phenocryst or crystal phenocryst) were completely or partially dissolved, hydrolyzed, and replaced; feldspar dissolution is most common
	Matrix dissolution	Dissolution, hydrolysis, replacement	Cribriform pores, uneven distributed in size
	Amygdala dissolution	Dissolution, hydrolysis, replacement	The amygdala pores are connected with fissures, dissolved from the amygdale edges and mineral cleavage, with the amygdala completely or partially dissolved

dissolved pores and micropores in matrix. Pores of dendritic morphology are often intergranular pores developed in volcanic breccia and tuff. Belted-shaped pores are mainly developed in volcanic breccia, forming intergranular pores and intergranular dissolved pores.

Physical property and pore structure

The porosity of our volcanic reservoirs changes from 2.3% to 21.8%, with the permeability from 0.015×10^{-3} μm^2 to 12.0×10^{-3} μm^2. The average porosity is 6.58%, and the average permeability is 0.85×10^{-3} μm^2 (all data were obtained from 207 samples). The buried depth of volcanic rock is all greater than 2900 m, the porosity are overall larger than 5%, few more than 10% when the maximum depth reaches 4200 m. There is no clear relationship between porosity or permeability and buried depth.

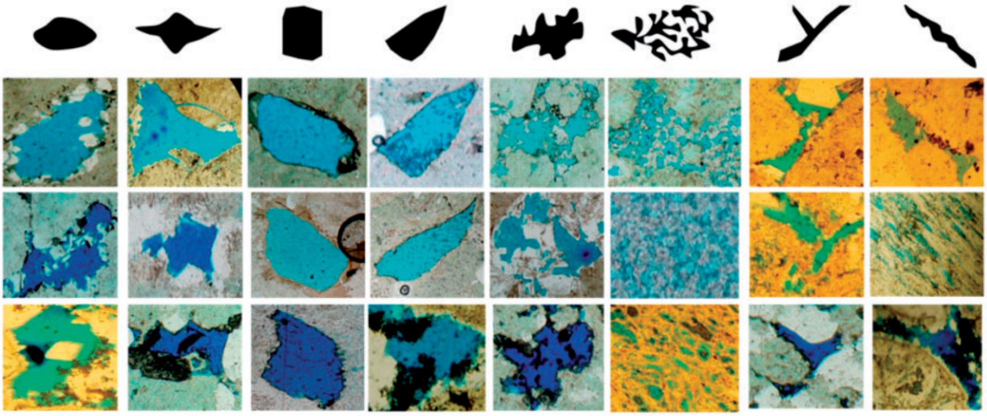

Figure 5. Optical photographs and the associated sketch map showing different types of pore morphology in the volcanic reservoirs. From the left to the right, they are elliptical, angular, rectangular, triangular, irregular, dispersive, dendritic, and belted pores. All the photos are captured from the thin section of different depths from well XS1, XS3, XS8, XS801 and XS9, with different magnification scale. These information are not labeled on the photos to avoid the disorder.

Pore structure has been obtained by the results of Hg-injection test. Capillary pressure curves of Hg injection showed three types: platform-shaped, slope-shaped, and upright-shaped. For volcanic breccia and vesicular rhyolite reservoirs, pore throats are relatively larger, which can control the resistivity, flow, and capillary pressure characteristics of the rock. And the sorting of pore spaces and connectivity is also the best. The capillary pressure curve is platform-shaped, which indicates low P_d (the displacement pressure), the platform is the widest, and the max S_{Hg} (the saturation of mercury) is comparatively high. Overall, the curve is close to the lower left, concave to the upper right, and the gentle section in the middle of the capillary pressure is very long (Figure 6). For basalt reservoirs, the capillary pressure curve is slope-shaped, which indicates low P_d, the sorting of pore throats is medium, and the max S_{Hg} is relatively high. In general, the curve is slightly closer to the upper right, concave to the lower left, and the gentle section is lower compared to other reservoirs. For tuff and andesite reservoirs, the capillary pressure curve is upright-shaped. P_d is high, and the max S_{Hg} is low. The curve is closer to the upper right, concave to the lower left, and the gentle section in the middle is not developed. All pores throat are formed by four processes during the diagenesis (Figure 7).

Discussion on diagenesis and porosity evolution

Generally, the diagenetic processes of volcanic rocks include condensation diagenetic stage, hydrothermal diagenetic stage, hypergenesis diagenetic stage, and burial diagenetic stage (Figure 8). During condensation stage, volcanic glass may get devitrification and vesicles shrinking. At hydrothermal stage, crystallization of numerous authigenic minerals and refilling of vesicles appear frequently. At hypergenesis stage, it is considered easier to have leaching dissolution during the breaks of volcanic eruption. There are relatively more diagenetic processes at the final burial stage, including compaction, cementation,

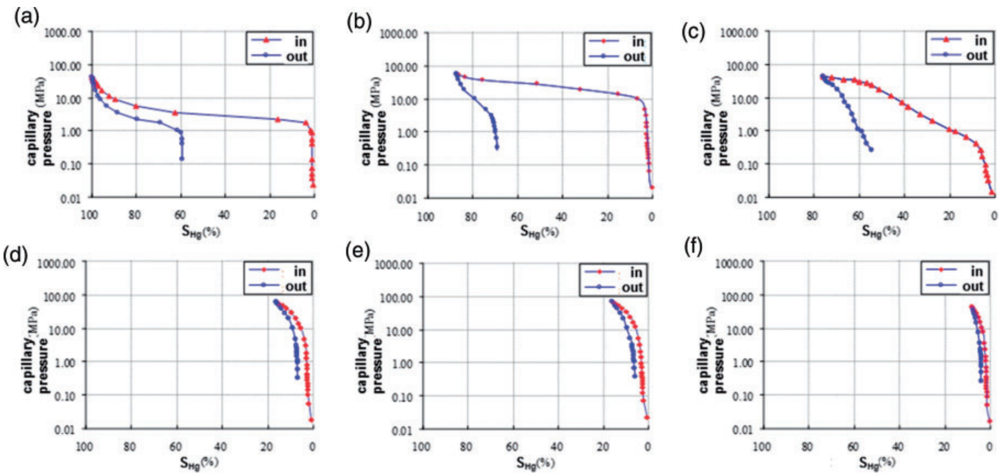

Figure 6. The capillary pressure curves of different rocks in the study area. (a) The platform-shaped curve of volcanic breccia in well CS2, 3799 m; (b) the slope-shaped curves of rhyolite in well CS4, 4311 m; (c) the slope-shaped curves of basalt in well CS2, 3857 m; (d) the upright-shaped curves of andesite in well CS7, 3632 m; (e) the upright-shaped curves of tuff in well CS4, 4430 m; and (f) the upright-shaped curves of tuff in well CS7, 3527 m.

metasomatism, dissolution, and recrystallization. These diagenetic processes of burial stage are the critical factors for forming primary storage space and pore structures before transformation stage (Zhu et al., 2018).

However, not all types of rocks will go through four-staged diagenetic process because of the complicated lithology of volcanic rocks. For example, in our study area, volcanic breccia and tuff had not undergone the condensation stage and hydrothermal stage. Therefore, different volcanic rocks experienced different diagenetic processes in our study area. In this article, diagenetic processes of three typical volcanic rocks have been discussed separately in detail.

Rhyolite

The diagenetic processes of rhyolite started with condensation. The most notable features of rhyolite diagenesis were volatile matter escaping at condensation stage and minerals, such as albite, quartz, and chlorite, refilling at hydrothermal stage. After the formation of primary pores, rhyolite pores experienced incomplete refilling of quartz, feldspar, and calcite as well as other minerals, eventually pores were completely refilled. We divided the diagenetic process of rhyolite into six sections as follows (Figure 9):

1. First, at condensation stage, several processes were developed in magma, such as phenocryst corrosion, condensation–crystallization, contraction, and volatile matter escaping. Meanwhile, mechanical compaction was developed in the early stage because of the gravity of rhyolite. The main primary pores of rhyolite were vesicles, and the assumed primary porosity may reach 25% to 30% based on recent facial porosity data of vesicles (including filled and unfilled).

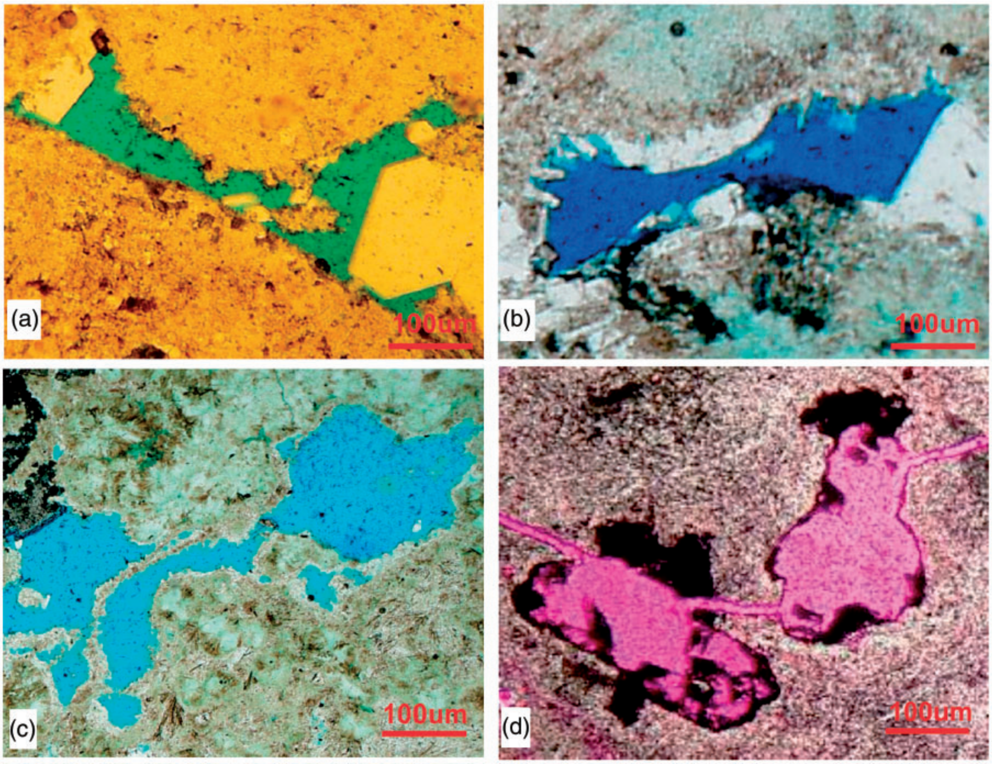

Figure 7. Optical photographs showing different throat of the pores in volcanic reservoirs. (a) Throat formed during the reduce of the pores by compaction, well XS401, 3797.55 m; (b) throat formed during the fill of the new crystal in the pores, well XS9, 3597.78 m; (c) throat formed by the dissolution of the pores, well XS901, 3864.2 m; and (d) throat formed by the fraction, well CS4, 4403 m.

2. Second, at hydrothermal stage, the primary vesicles were filled by hydrothermal fluid of albite, quartz, chlorite, and carbonate minerals in order. After observing the fulfilling time and filled percentage of those minerals under thin section, it was confirmed that the vesicular porosity was reduced by 10% to 15%.
3. After entering the hypergenesis stage, rhyolite had weak mechanical compaction due to its volcanic texture. However, the feldspar phenocryst minerals and matrix minerals underwent variable degrees of kaolinization, sericitization, and calcitization. And the weak quartz overgrowth began to appear in the rock, which had a destructive effect on vesicles. Yet during the previous condensation stage, the recrystallization and devitrification of matrix minerals had constructive effect on vesicles; therefore, the porosity had weak change during hypergenesis stage.
4. At the early stage of burial stage, due to the further quartz overgrowth and carbonate minerals cementation, the porosity loss was relatively large. By assuming the percentage of quartz overgrowth, the porosity of burial stage was reduced by 5% to 10%, and porosity was reduced to 10%.
5. At the middle stage of burial stage, large amount of organic acid was formed after the maturation of the source rock. Organic acid created certain degree of dissolution on

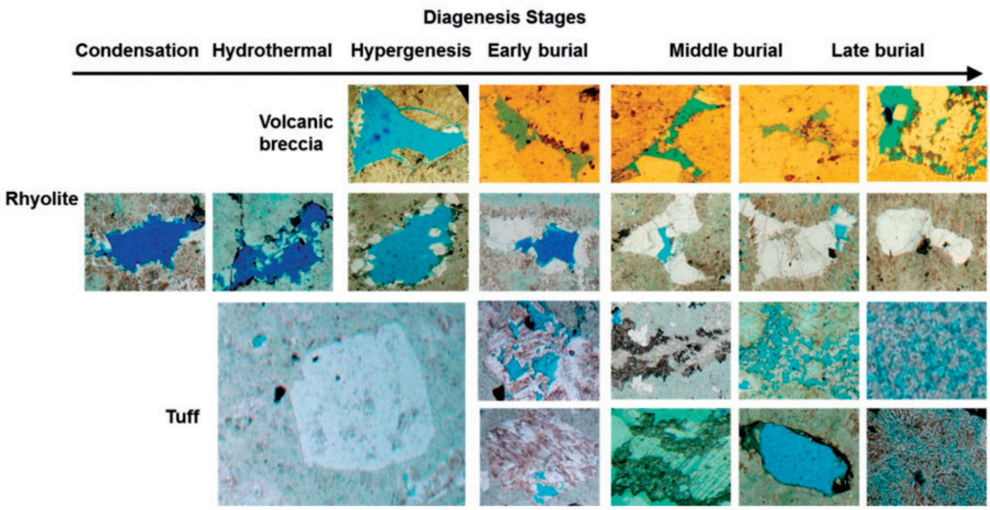

Figure 8. The sketch photograph showing the changes in different volcanic rocks during different diagenesis stages since its eruption from the volcanic vent. The evolution is showed laterally for each kind of rocks.

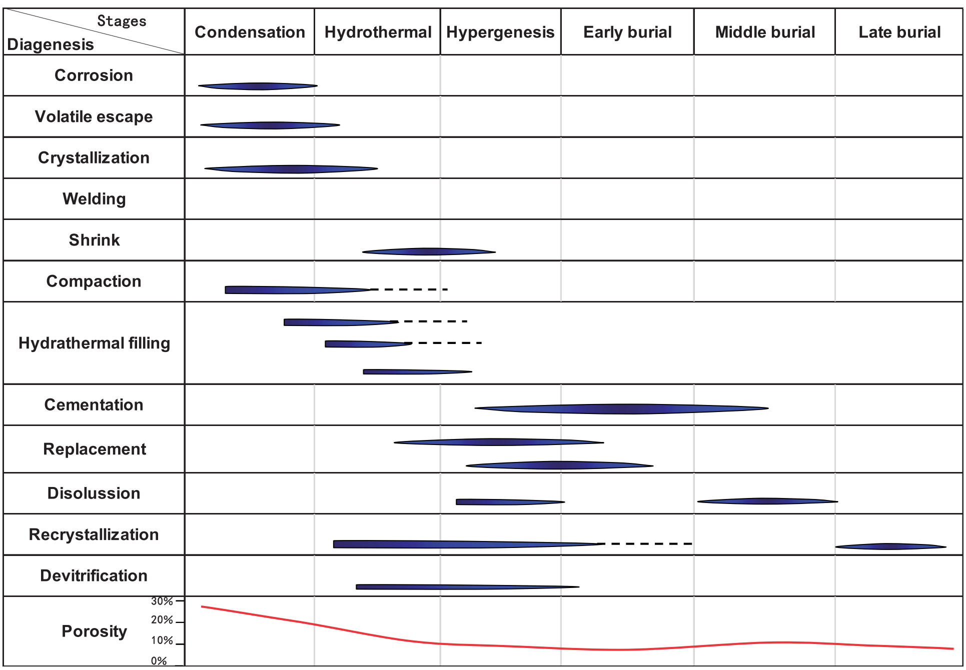

Figure 9. The sketch map showing the diagenesis change and porosity evolution in rhyolite during different diagenetic stages.

rhyolite phenocryst and matrix and may expand the early well-connected pores through dissolving; both two processes had constructive effect on porosity. Porosity was increased by 3% to 5%.

6. Finally, in the late burial stage, cementation and metasomatism occurred. The final porosity of rhyolite remained around 8% to 12%.

Crystal tuff

Crystal tuff is developed with pyroclastic texture, the main differences from rhyolite are as follows: first, the diagenesis of crystal tuff started later than rhyolite, and the porosity evolving began at hypergenesis stage; second, the crystal tuff had strong late dissolution, and mold pores were formed in feldspar and other phenocrysts through this strong dissolution. And spherulitic micropores were developed through matrix recrystallization. In conclusion, the primary porosity of crystal tuff is not developed, and the porosity evolving remains at a lower level compared to rhyolite (Figure 10).

1. During the condensation and hydrothermal stage, in addition to the phenocryst corrosion and contraction–condensation, the crystal tuff had no other clear diagenesis, and the pore evolution had not yet begun.
2. After entering the hypergenesis stage, the major diagenesis of crystal tuff was mechanical compaction, freshwater leaching, and metasomatism. The phenocryst and matrix started kaolinization and possibly weak dissolution. At this stage, mechanical compaction had

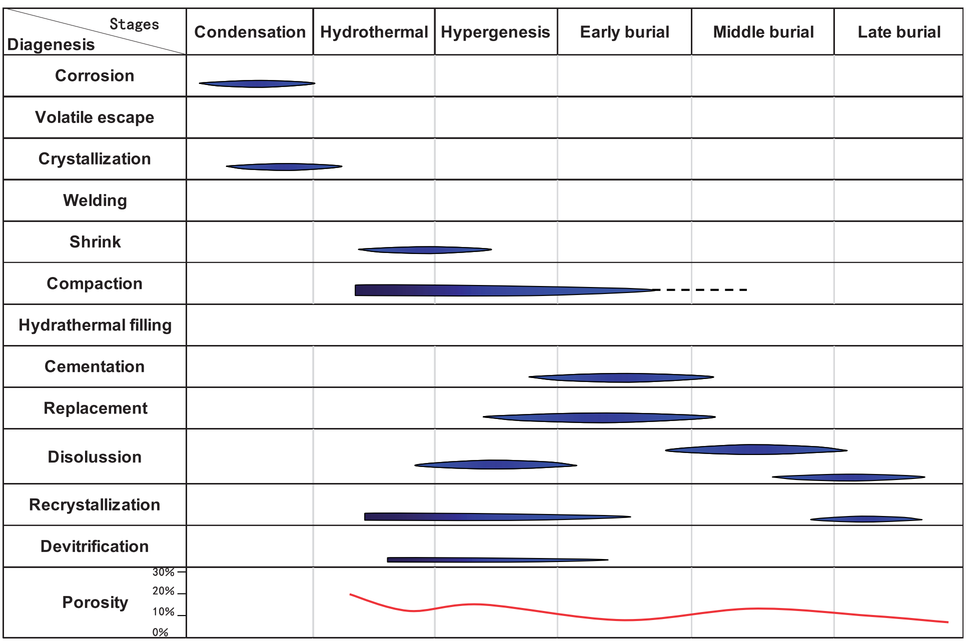

Figure 10. The sketch map showing the diagenesis change and porosity evolution in tuff during different diagenetic stages.

the greatest influence on pore evolution. After compaction, the primary porosity may be rapidly reduced from 20%, which was accumulated initially, to about 10%.

3. In the early period burial stage, the compaction was continued but gradually began to weaken. Carbonate cementation caused more porosity loss, and the porosity was reduced to less than 10%.
4. After entering the middle burial stage, organic acidic created stronger dissolution on crystal tuff phenocryst and matrix, which increased porosity significantly. The tectonic structural fracture also improved reservoir storage by increasing porosity. Therefore, during this stage, the porosity of crystal tuff was increased to 10% to 12%.
5. In the late burial stage, there was no other strong diagenetic effect on pores evolution except for continued compaction and matrix recrystallization.

Volcanic breccia

Volcanic breccia is also developed with pyroclastic texture as crystal tuff; however, there is still some difference compared with crystal tuff. Volcanic breccia grew with more primary porosity at the early stage of diagenesis, and cementation became stronger while dissolution was weakening at the late stage. Detailed evolution processes are explained as follows (Figure 11):

1. Same as crystal tuff, during condensation and hydrothermal period, there was no other strong diagenesis apart from phenocryst dissolution as well as condensation–contraction. The porosity evolution had not been started yet.

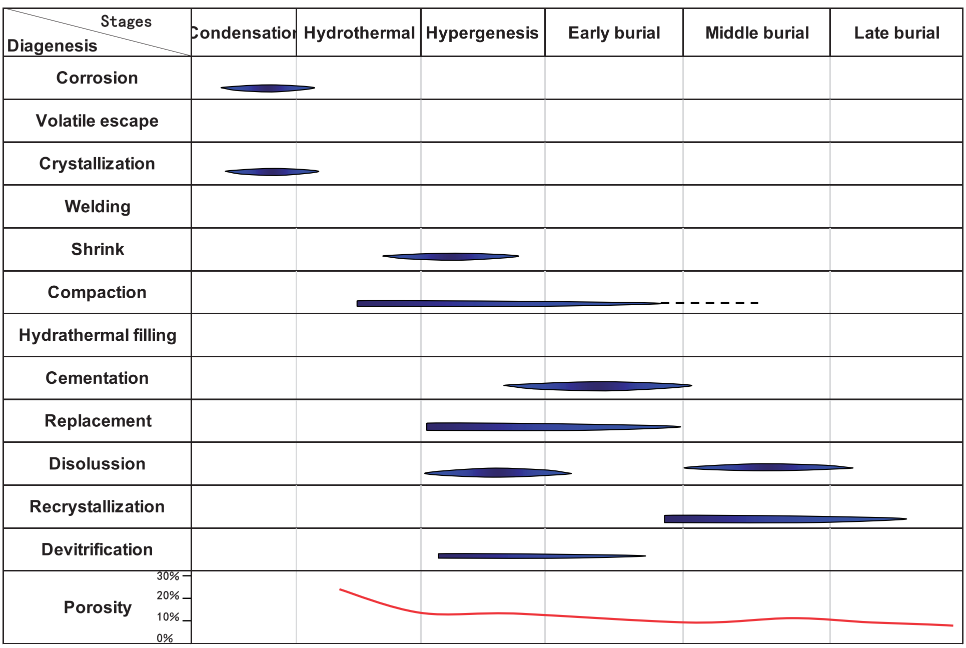

Figure 11. The sketch map showing the diagenesis change and porosity evolution in volcanic breccia during different diagenetic stages.

2. During the hypergenesis stage, the major diagenetic processes of volcanic breccia were mechanical compaction, freshwater leaching, and metasomatism. Kaolinization appeared on the surface of volcanic breccia crusts and weak dissolution on rock debris. Although the primary porosity was well formed at the beginning, the porosity was reduced from 25% to 15% after mechanical compaction.
3. At the early burial stage, compaction continued but was getting weaker gradually. The primary pore space was fulfilled by strong feldspar or quartz overgrowth and carbonate cementation, and the porosity was reduced to 10%.
4. At the middle burial stage, organic acidic dissolution was much weaker on volcanic breccia compared with crystal tuff. Only partial rock debris was dissolved, and later primary intergranular pores were created. The intragranular pores were difficult to form here. Therefore, dissolution caused slightly porosity expansion.
5. At the late burial stage, compaction continued, but there was no other diagenesis that effects pores evolution vigorously.

Factors controlling those diagenetic differences

In conclusion, there are two major differences between diagenesis and porosity evolutions of above three types of rocks: First, the starting time of diagenetic processes is different for rhyolite, volcanic breccia, and crystal tuff. For rhyolite, diagenesis began relatively earlier. During eruption–condensation period, there were already volatile matter escaping as well as phenocryst corrosion and condensation–crystallization. But for crystal tuff and volcanic breccia, diagenesis started later, usually diagenesis and pores evolution started from the hypergenesis stage. Only small portion of debris minerals had diagenetic changes during condensation and hydrothermal stage. Second, the diagenesis types are dependent on lithology of volcanic rocks, and the physical or chemical varies widely during different stages. For example, compaction–pressure dissolution was the easiest diagenesis to be developed for volcanic breccia, followed by crystal tuff, then rhyolite. As for dissolution, it was strongest during the middle burial period for crystal tuff, but it was relatively weaker for rhyolite and volcanic breccia, followed by tight rhyolite. In this article, the author argues that the major difference of diagenesis between different volcanic rocks is mainly related to the rock genesis, composition, and structure in the study area.

Rock genesis refers to the variable ways of rock consolidation. Volcanic lavas are consolidated through condensation, with pyroclastic rock through compaction, and pyroclastic lava through compaction–condensation, mainly condensation (Cas and Wright, 1987). Consolidated rocks are similar with clastic rocks, they have framework grains, pores, and interstitial materials. For consolidated rocks, compaction–pressure dissolution plays a more important role in the diagenetic change of volcanic rocks. Moreover, fluids inside rocks are also moving actively, which make diagenesis easier to occur. During the process of rocks consolidating through condensation, many unique changes occurred in the process of magma erupting from the volcanic channel to the surface ground, including volatile matter escaping, condensation–crystallization, contraction, and erosion. After the rocks were consolidated, matrix or phenocryst did not exist anymore, neither did the "framework grains-pores-interstitials" structure. Compaction caused no effect on rocks, in other words, compaction process did not occur.

The influence of rock composition and structure on diagenesis is easier to understand. If rock was composed by different magma, like mafic and intermediate or silicic magma, crystallized components were also different, including phenocryst mineral, the matrix components, hydrothermal fluids, and other fluids (Klug and Cashman, 1996). Metasomatism and dissolution have variable level of difficulty to occur if the components of magma are different. Moreover, the types and features of metasomatism, cementation, and filling effects are also different. Apart from rock composition, rock structure also has certain influence on fluid fluidity, which further cause "water–rocks" chemical reaction. For instance, because the volcanic lavas had relatively poor fluidity, the dissolution effect was weak; meanwhile fluids were difficult to escape from rocks, and therefore, volcanic lavas had strong cementation, fulfilling, and recrystallization (Jiang and Wang, 2010; Lei et al., 2008; Liang et al., 2011; Luo et al., 2013; Zhao et al., 2009). Hence, lithologies of volcanic reservoirs have significant effects on diagenesis and further on pores evolution. In order to evaluate and forecast volcanic reservoirs systematically, the critical task is to predict the vertical and horizontal distribution of rock lithologies so that potential reservoirs could be located precisely.

Conclusion

1. In this study area, lithologies of volcanic rocks include tuff, volcanic breccia, ignimbrite, rhyolite, basalt, and andesite (Figure 3). Among them, rhyolite as well as tuff and volcanic breccia are the major volcanic reservoirs, they account for the largest portion in total. Inside these reservoirs, there are 10 different types and sizes of both primary and secondary porosity, including volcanic primary vesicles, residual vesicles, matrix micropores, intergranular dissolved pores, intergranular dissolved pores, mold pores, matrix pores, and recrystallized micropores.
2. Different volcanic rocks experience six stages of diagenesis, including condensation stage, hydrothermal stage, hypergenesis stage, early, middle, and late burial stages. Multiple diagenetic processes developed during these six stages, such as magma condensation–recrystallization, volatile matter escaping, hydrothermal fulfilling, magma erosion and cementation, dissolution, metasomatism, and recrystallization. Different volcanic rocks had different diagenetic features and pores evolution process. Rhyolite mainly underwent magma condensation–recrystallization, hydrothermal fluid fulfilling vesicles, feldspar phenocrysts kaolinization and sericitization, felsic matrix carbonation, matrix devitrification and recrystallization, and dissolution of feldspar phenocrysts and felsic matrix. As for volcanic breccia, it usually experienced compaction, quartz and calcite filling the primary pores between volcanic breccias, and dissolution of volcanic debris and tuff matrix. Volcanic tuff underwent compaction, felsic matrix carbonation, and kaolinization as well as dissolution of feldspar with felsic matrix.
3. In this study area, the major difference between diagenesis process and rock lithology is mostly due to rock genesis, composition, and structure. Therefore, in the progress of evaluating and predicting volcanic reservoirs, it is necessary and critical to distinguish and analysis volcanic diagenesis and pores evolution based on their different composition and structure; more detailed vertical and horizontal distribution of lithology is also required.

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