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ORIGINAL PAPER

Reservoir characteristics, formation mechanisms and petroleum exploration potential of volcanic rocks in China

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Abstract Characterized by complex lithology and strong heterogeneity, volcanic reservoirs in China developed three reservoir space types: primary pores, secondary pores and fractures. The formation of reservoir space went through the cooling and solidification stage (including blast fragmentation, crystallization differentiation and solidification) and the epidiagenesis stage (including metasomatism, filling, weathering and leaching, formation fluid dissolution and tectonism). Primary pores were formed at the solidification stage, which laid the foundation for the development and transformation of effective reservoirs. Secondary pores were formed at the epidiagenesis stage, with key factors as weathering and leaching, formation fluid dissolution and tectonism. In China, Mesozoic–Cenozoic volcanic rocks developed in the Songliao Basin and Bohai Bay Basin in the east and Late Paleozoic volcanic rocks developed in the Junggar Basin, Santanghu Basin and Tarim Basin in the west. There are primary volcanic reservoirs and secondary volcanic reservoirs in these volcanic rocks, which have good accumulation conditions and great exploration potential.

Keywords Volcanic reservoirs · Diagenesis · Formation mechanism · Hydrocarbon exploration

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1 Introduction

As sites for hydrocarbon accumulation, reservoirs are very important for research on petroliferous basins. In recent years, AAPG conferences have chosen reservoir studies as a topic and one of the major trends in studies of petroliferous basins. For a long time, research on reservoirs mostly focused on rocks related to sedimentary processes. Volcanic rocks, seldom regarded as reservoirs, have not been looked into sufficiently (Rohrman 2007; Lenhardt and Götz 2011).

Extensively distributed in a number of petroliferous basins around the world, volcanic rocks are one type of hydrocarbon-bearing rocks, and they may form hydrocarbon reservoirs (Bashari 2000; Chen et al. 2014). Since the first discovery of hydrocarbon reservoirs in volcanic rocks in the San Juan Basin, California in 1887, exploration history has extended for 120 years. Up to now, over 300 hydrocarbon reservoirs or oil/gas shows related to volcanic rocks have been identified around the world. Among them, 169 hydrocarbon reservoirs have proved reserves (Zou et al. 2008). These volcanic reservoirs have the following characteristics: (1) formed mainly in the Mesozoic–

Cenozoic continental margin settings; (2) lithological, dominated by basalt reservoirs (accounting for 32 %) and andesite reservoirs (accounting for 17 %); (3) reservoir spaces are mainly primary or secondary pores, and the common-developed fractures improve reservoir properties; and (4) generally small-scale reservoirs, but can also be high-production wells.

With progress in hydrocarbon exploration around the world and more and more discoveries of volcanic reservoirs, volcanic rocks have attracted the interest of scholars and the petroleum industry as a new domain for hydrocarbon exploration (Zhao et al. 2008; Zou et al. 2008). In the late 1990s, volcanic rock reservoir geology emerged as an important marginal discipline (Zhu et al. 2010a, b), which studies the macro distribution, internal structures, reservoir parameter distribution and pore structures in volcanic rocks, together with dynamic changes of reservoir parameters during development of fields in volcanic rocks, for the purpose of guiding exploration and development of oil and gas fields.

At the same time, petroleum geology theories and techniques related to volcanic rocks also have experienced rapid development (Sruoga and Rubinstein, 2007; Farooqui et al. 2009; Zhang et al. 2011; Zou et al. 2012a, b; Dong et al. 2013; Du et al. 2013). In the south Nagaoka gas field in Niigata, Japan, gamma ray, compensated formation density and compensated neutron logs were used together to successfully identify reservoirs in Miocene "Green tuff"—rhyolite volcanic rocks in the Qigu Formation (Yagi et al. 2009). Generally speaking, research on volcanic reservoirs is more difficult than clastic and carbonate reservoirs. Consequently, it emphasizes the comprehensive application of multiple disciplines, as petroleum geology, volcanology, petrology and reservoir physics theories, together with technologies as gravity-magnetic survey, electric prospecting, seismic, logging, mathematic geology and computer technology (Pan et al. 2008; Zhu et al. 2010a, b; Chen et al. 2014).

2 Volcanic reservoir characteristics in China

Volcanic rocks, the product of a series of volcanic activities after cooling, solidification and consolidation, are significantly different from sedimentary rocks in formation conditions, development environment and distribution pattern. Consequently, characteristics of hydrocarbon reservoirs in volcanic rocks are quite different from those in sedimentary rocks.

2.1 Lithological features of volcanic reservoirs in China

Sedimentary basins in China developed under various regional tectonic backgrounds (Lü et al. 2004; Luo et al. 2012; Zhao et al. 2009; Xie et al. 2010) have a variety of reservoir volcanic rocks (Mao et al. 2010). Among them, lava rocks mainly include basalt, andesite, dacite, rhyolite, trachyte, etc.; pyroclastic rocks mainly include agglomerate, volcanic breccia, tuff and welded pyroclastic rocks. Mesozoic volcanic reservoirs in eastern China mostly generated in the Late Jurassic to Early Cretaceous, with basic to acidic rocks, but mostly are acidic (Fig. 1); Cenozoic volcanic reservoirs in eastern China mainly include those in the Jiangling Sag of the Jianghan Basin, Jiyang Sag and the eastern part of the Liaohe Sag, and lithologically, there are acidic to basic rocks, but mostly are meso-basic rocks (Zhao et al. 2008). Volcanic rocks in western China are dominated by meso-basic rocks, such as the Permian Formation in the Tarim Basin, Carboniferous Batamayineishan Formation in the Junggar Basin and Permian Jiamuhe Formation in the Tuha Basin and the Carboniferous-Permian system in the Santanghu Basin (Fig. 1) (Zhou et al. 2010; Zhang et al. 2013a, b).

2.2 Types and features of reservoir space in volcanic rocks in China

Compared with sedimentary rocks, volcanic rocks are much more complicated in reservoir space types and features. According to observations and research on large quantities of cores and thin sections, volcanic reservoir spaces can be classified into three major categories: primary pores, secondary pores and fractures (Table 1). Primary pores are predominantly composed of pores formed during the eruption of volcanic material, residual pores incompletely filled by amygdaloidal bodies, intercrystalline micro-pores and pores among volcanic breccia (Fig. 2a, b). Secondary pores mainly include volcanic glass devitrification pores, together with various mineral and particle dissolution pores and cavities (Fig. 2c, d). Fractures can be formed by the following three reasons: bursting fractures and contraction fractures formed due to volcanism and cooling (Fig. 2a); structural fractures formed by volcanic rocks deformation and slippage induced by tectonic stresses (Fig. 2e); and dissolution fractures formed by the dissolution of formation fluids during weathering, leaching and burial processes (Fig. 2f).

Typical samples of volcanic reservoir rocks from the Yingcheng Formation in the Songliao Basin (110 samples from 49 wells) and the northern Xinjiang Carboniferous (53 samples from 15 wells) were observed by optical microscopy, combined with quantitative analyses. The results show that reservoir spaces in both areas are dominated by air pores, dissolution pores and micro-fractures. At the same time, they have significant differences in percentages. Volcanic rocks of the Yingcheng Formation in the Songliao Basin are dominated by air pores (38 %) and

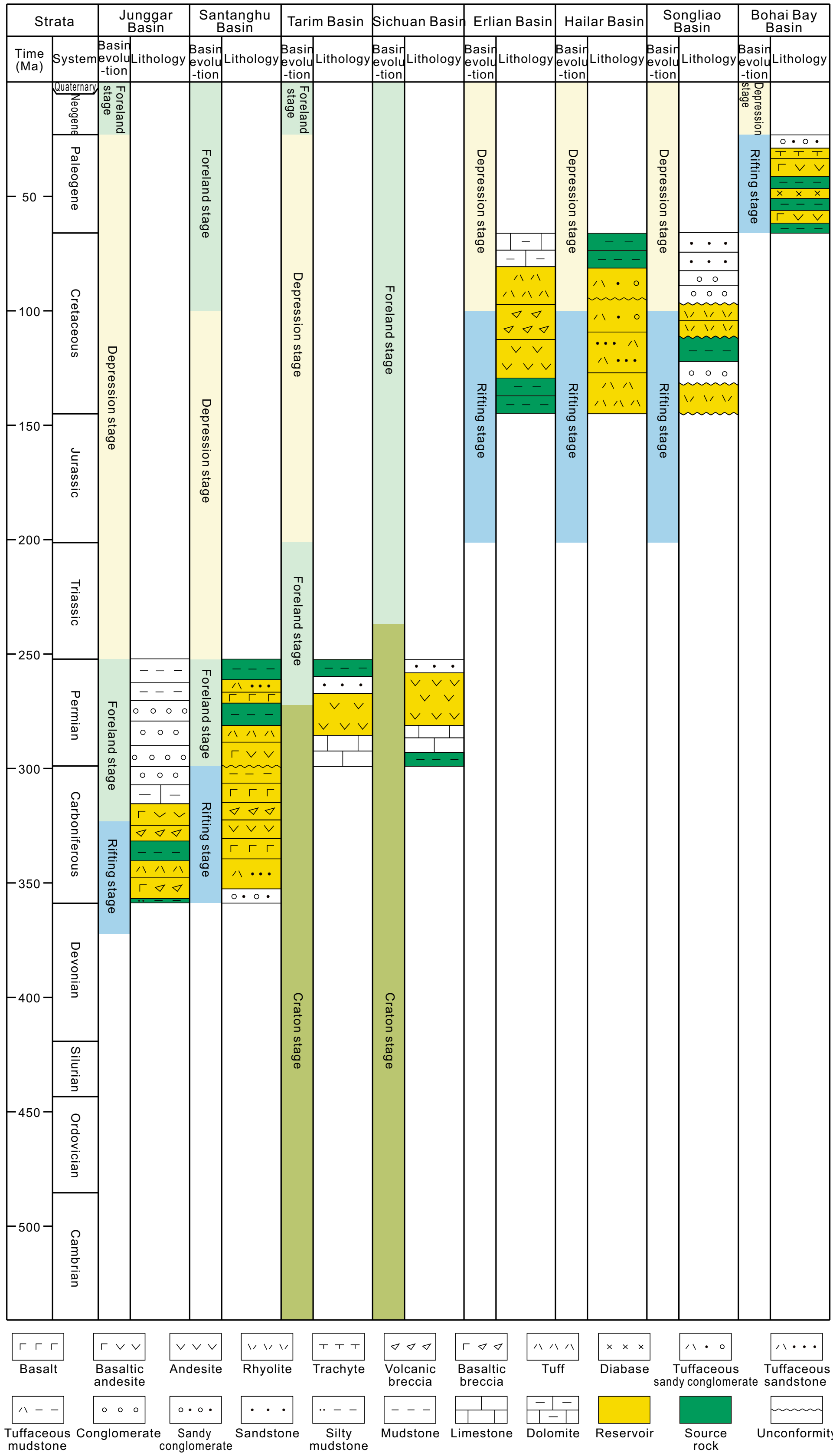

Fig. 1 Lithology of volcanic rocks and evolution of petroliferous basins of China

Table 1 Classification and features of reservoir space of volcanic rocks in China

Classification		Origin	Features	Corresponding lithological features	Oiliness
Primary pores	Primary air pores	Formed due to expansion of gas during diagenetic process	Mostly distributed at bottom and top of lava-flow layers in different sizes and shapes	Volcanic breccia, lava	Good in those connected with pores and fractures
	Residual air pores	Pores formed due to incomplete filling of pores by secondary minerals	Also known as semi-filling pores	Basalt, volcanic breccia	Good in those connected with pores and fractures
	Intergranular pores	Residual pores formed after diagenetic compaction between clastic particles	Mostly in pyroclastic rocks	Volcanic breccia, agglomerate, volcanic sedimentary rocks	Good
	Intercrystal, inner-crystal pores	Pores in framework of rock-forming minerals, augite, plagioclase and phenocryst minerals, mostly with cleavage. They are inner-crystal pores themselves	Mostly distributed in central parts of lava-flow layers with minor pores	Lava, pyroclastic rocks	Good
Secondary pores	Devitrification pores	Formed by vitric matter after devitrification	Micro-pores, but with favorable connectivity	Spherulitic rhyolite, ignimbrite	Fairly good reservoir space
	Phenocryst dissolution pores	Phenocryst may generate pores due to dissolution of fluids. Such dissolutions may develop along cleavage faces	Irregular in pore shape, mostly in bay shape and dominated by inner-crystal pores	Andesite	One of the most important reservoir space
	Dissolution pores in amygdaloidal bodies	Dissolution pores generated due to alternation and dissolution of filling materials in air pores	Irregular in pore shape with poor connectivity	Lava	Favorable hydrocarbon-bearing features
	Dissolution pores in matrix	Devitrification of vitric matter in matrix or dissolution of microcrystal feldspar	Fine pores, mostly dissolution pores with certain connectivity	Various lava and melted tuff	Favorable reservoir formations
	Dissolution pores among breccia	Formed due to weathering, leaching, dissolution and other epigenetic actions	Developed along fractures, cracked clastics and structural highs	Basalt, andesite, breccia	Good hydrocarbon-bearing features
Fractures	Solidification contraction fractures	Micro contraction fractures formed during solidification and crystallization of lava	Columnar jointing and split in open or facial configuration with minor dislocations	Volcanic breccia, andesite, trachyte	Generally good
	Explosion fractures	Self-cracking or concealed eruption	Restorable	Self-cracking breccia, lava and secondary volcanic rocks	Good
	Structural fractures	Micro-fractures generated under tectonic stress	Developed near faults, flat and straight, mostly high angle fractures	Basalt, andesite	Related to timing of tectonic activities
	Weathering fractures	Usually connected with dissolution pores, fractures and structural fractures to cut rocks into debris of various sizes	Connected with dissolution pores, fractures and structural fractures	Pyroclastic rocks, volcanic breccia	Good
	Dissolution fractures	Weathering and leaching, dissolution by formation fluid	Dissolution and extension of original fractures	Amygdaloidal andesite, volcanic breccia	Fairly good hydrocarbon-bearing features

Modified after Du et al. (2013) and Zou et al. (2012a, b)

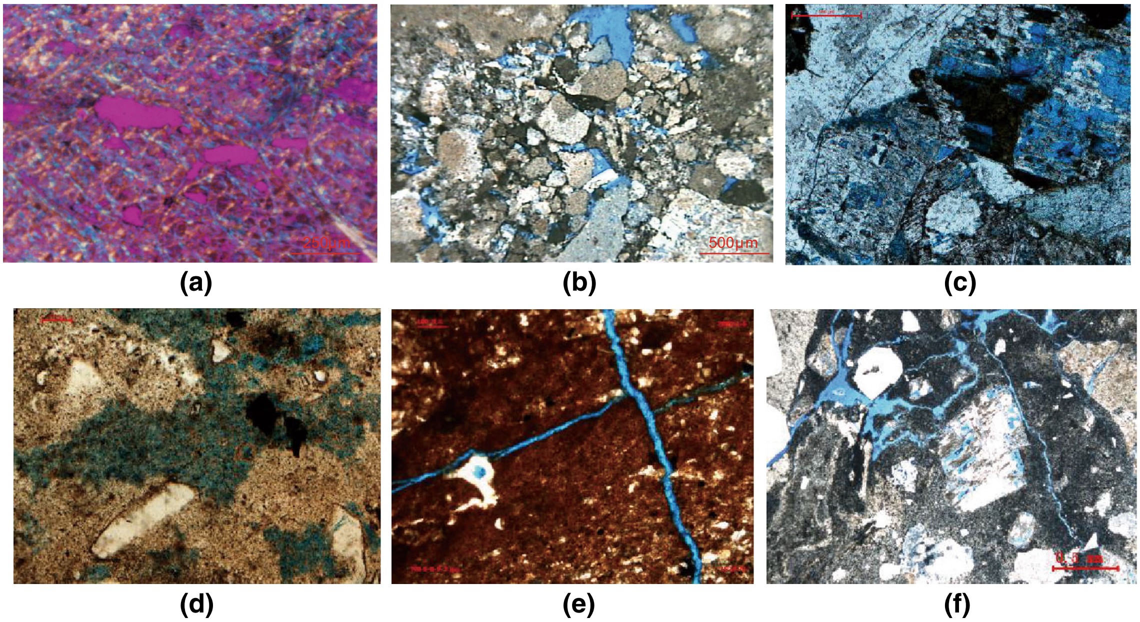

Fig. 2 Types and microscope photos of reservoir spaces in volcanic rocks. **a** Rhyolitic ignimbrite, air pores and contraction fractures, well Madong-1, 4266.85 m, ×2.5. **b** Volcanic breccia, intergranular pores, well Dixi-5, 3649.19 m, ×4 (+). **c** Lava, feldspar phenocryst, dissolved pores, well Huang-95, 2908.00 m, ×5 (−). **d** Quartz porphyry, matrix dissolution pores, well Mana-1, 5166.0 m, ×10 (−). **e** Tuff, structural micro-fractures, well Niudong-9-8, 1524.75 m, ×10 (−). **f** Tuff, weathering and leaching dissolution pores and fractures, well Di-403, 3818.55 m, ×4

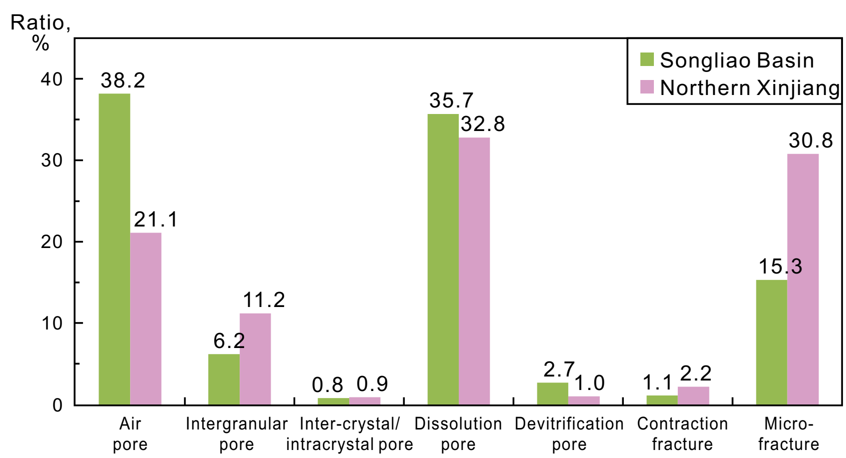

Fig. 3 Pore types and average contents in typical volcanic reservoirs of China

dissolution pores (36 %) (Fig. 3), whereas Carboniferous volcanic rocks in the Northern Xinjiang have mainly dissolution pores (33 %) and micro-fractures (31 %) (Fig. 3).

2.3 Physical properties of volcanic rocks in China

There are a variety of reservoir spaces in volcanic reservoirs. Different reservoir spaces may combine with each other to form pore-fracture dual-media reservoirs which have complicated pore structures, leading to widely variable physical properties and severe heterogeneity. Physical properties of volcanic rock samples (112) from the Junggar, Santanghu, Songliao and other basins show that pyroclastic rocks, lava rocks and hypabyssal intrusive rocks can serve as effective reservoirs, mostly with medium to high porosity, low to medium permeability, high heterogeneity, and poor correlation between porosity and permeability. Porosity may be over 30 %, with 10 % on average, whereas permeability may display intense heterogeneity with the maximum over 1,000 × 10^{-3} μm^2. But on the whole, the permeability is quite low, mostly less than 1 × 10^{-3} μm^2 and a large portion may be less than 0.01 × 10^{-3} μm^2 (Fig. 4).

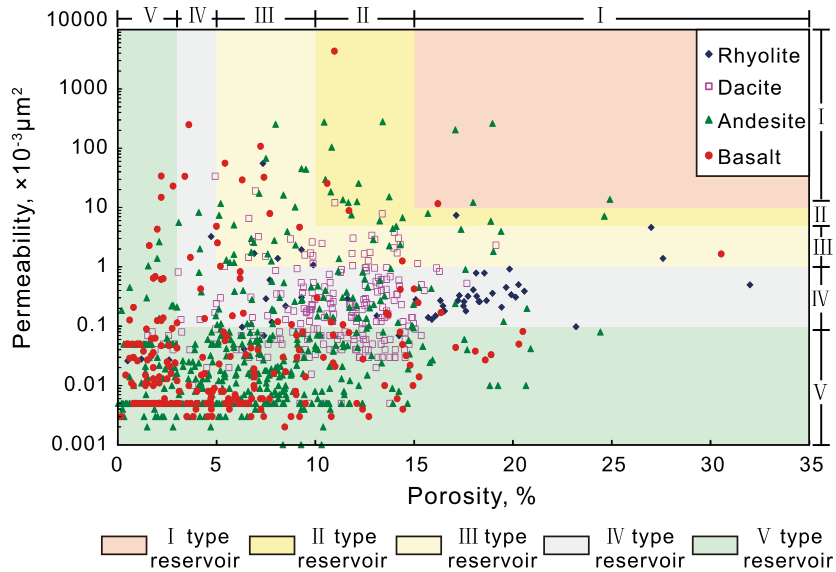

Fig. 4 Correlation between porosity and permeability of volcanic rocks (978 core samples, reservoir classification according to SY/T 6285-2011)

3 Origin and controlling factors of volcanic reservoirs in China

Compared with clastic reservoirs, volcanic reservoirs are more complex in pore types. Intercrystal pores, contraction pores and other primary pores formed after cooling of igneous rocks are not much affected by compaction, but complicated raw minerals and their combination may experience dramatic changes due to hydrothermal fluids during tectonic evolution and diagenetic burial. These changes may affect diagenesis routes of volcanic rocks and diagenetic products, resulting in different pores and throats occurrence and storage properties. In the end, such differences may directly affect the formation and evolution of high-quality reservoirs in volcanic rocks (Surour and Moufti 2013; Borgia et al. 2014; Caricchi et al. 2014). Therefore, it can be seen that volcanic reservoirs are the combined product of volcanism, tectonization, diagenesis, fluids, epidiagenesis, burial transformation and many other factors.

3.1 Diagenesis evolution of volcanic reservoirs in China

Due to their special features, volcanic reservoirs have obvious stages and periods in diagenesis and evolution (Sruoga and Rubinstein 2007). Diagenesis is distinctive in different stages and periods. Consequently, it is possible to divide the diagenesis processes of volcanic rocks into several stages and further into different periods (Table 2).

Since different diageneses may evolve constantly with changes in diagenetic environments, some diagenesis may happen during different diagenetic stages. In addition, different sedimentary basins have various burial–tectonic–thermal evolution history, so volcanic rocks in different basins would experience quite different diageneses at different stages. Therefore, different volcanic reservoir types have their unique diagenesis sequence and diagenetic stage.

Research on volcanic reservoir diagenesis of different periods and types in different basins shows that there are two major diagenesis sequences in volcanic rocks in China: eruption—burial diagenesis sequence and eruption—weathering—burial diagenesis sequence.

(1) Eruption—burial diagenesis sequence of volcanic rocks in the Yingcheng Formation, Songliao Basin. Eruption—burial diagenesis sequence includes volcanic eruption, cooling, solidification and consolidation, and subsidence and burial by sediments. Reservoir spaces are dominated by primary pores generated during eruption, cooling, solidification and consolidation of volcanic rocks, and these are primary volcanic reservoirs. The Cretaceous Yingcheng volcanic reservoir in the Songliao Basin is a typical reservoir of this type (Jin et al. 2010; Cai et al. 2012).

After eruption in the Early Cretaceous, the Yingcheng Formation volcanic rocks in the Songliao Basin were formed after experiencing dissolution, cooling, crystallization and some other consolidation (approximately 156–125 Ma) (Sun et al. 2008; Meng et al. 2010; Shao et al. 2013; Xiang et al. 2013; Zhang et al. 2013a, b). Then the formation was covered directly by overlying sedimentary strata after short periods of hydrothermal fluids and weathering and leaching between eruption intermissions. During these periods, the formation experienced no less than two stages of large-scale

Table 2 Diagenetic stages of volcanic rocks

Diagenetic stage		Diagenesis	Mechanisms of diagenesis	Diagenesis markers	Pore types
Stage	Period				
Cooling and solidification stage	Volcanic active period	Explosion and cracking	Eruption, cracking and explosion of volcano	Pyroclastic rocks of various compositions and particle sizes	Air pores, intergranular pores, explosion fractures, contraction fractures, intercrystalline pores
	Solidification period	Crystalline differentiation	Differentiation, separation and crystallization of lava	Volcanic rocks with different crystals and mineral compositions	
		Solidification	Solidification and contraction	Volcanic rocks contraction fractures	
Re-construction stage	Hydrothermal period	Alteration	Changes in temperatures in uprising hot fluids in deep layers	Chlorite and zeolite	Intercrystalline micro-pores in clay minerals, pores in amygdaloidal bodies, residual pores, dissolution pores, dissolution fractures
		Filling	Crystallization and precipitation of minerals carried out by volcanic hydrothermal solution	Chlorite, zeolite filling	
		Dissolution	Dissolution, alternation of volcanic hydrothermal solution	Chlorite, zeolite solution pores	
	Weathering & leaching period	Weathering, breaking	Thermal expansion of rocks	Weathering fractures	Weathering fractures
		Leaching dissolution	Leaching and dissolution of rocks	Intergranular, inner-granular solution holes, dissolution fractures	Dissolution pores, dissolution fractures
	Burial period	Compaction	Compaction	Intergranular, intercrystalline contacts and modification of debris	
		Tectonization	Tectonic stress	High angle fractures, near horizontal fractures, reticular fractures	Structural fractures
		Dissolution	Dissolution by formation water and organic acid	Huge amounts of secondary solution holes	Matrix solution holes, phenocryst solution holes, intergranular dissolution pores, dissolution fractures
		Alteration	Increase of formation temperatures and pressures, together with activities of formation fluids	Zeolite, chlorite, clay and other associated minerals	
		Filling and cementation	Formation fluid dissolution, mineral precipitation	Filling and cementation of zeolite, chlorite, clay and other minerals	
		Devitrification	Increase of formation temperatures and pressures	Felsitic texture, cryptocrystalline texture after devitrification	

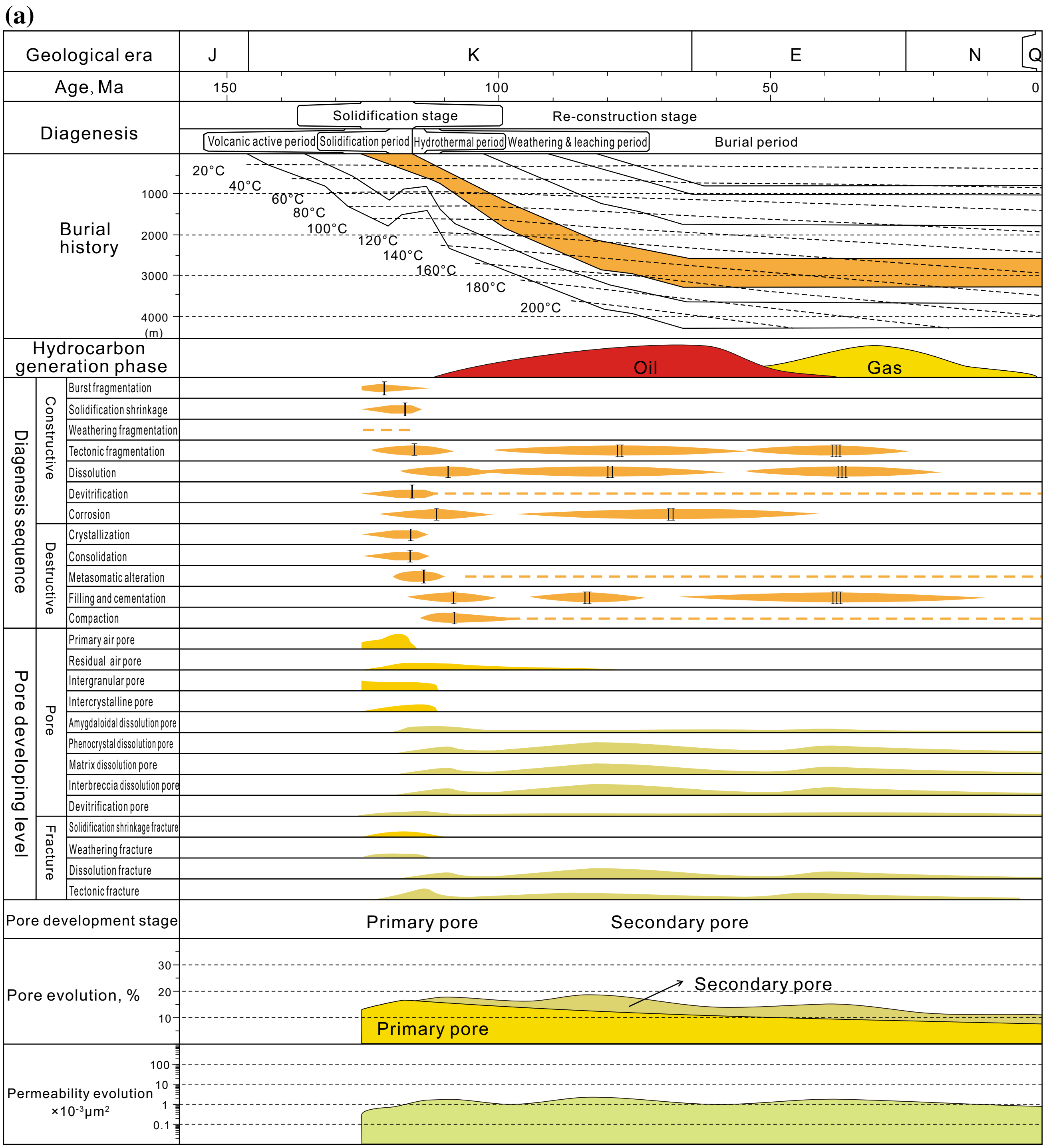

Fig. 5 Diagenesis and porosity evolution of typical volcanic reservoirs in China. **a** Cretaceous volcanic rocks of the Yingcheng Formation in the Songliao Basin. **b** Carboniferous volcanic rocks in the Junggar Basin

secondary dissolution, two stages of hydrocarbon charge, three stages of fracture generation, 2–3 stages of siliceous cementation, three stages of carbonate cementation, 2–3 stages of chlorite cementation and formation of zeolite, albite, fluorite and other secondary minerals (Qin et al. 2010; Sun et al. 2012; Luo et al. 2013) (Fig. 5a).

(2) Eruption—weathering—burial diagenesis sequence of Carboniferous—Permian volcanic rocks in northern Xinjiang.

(b)

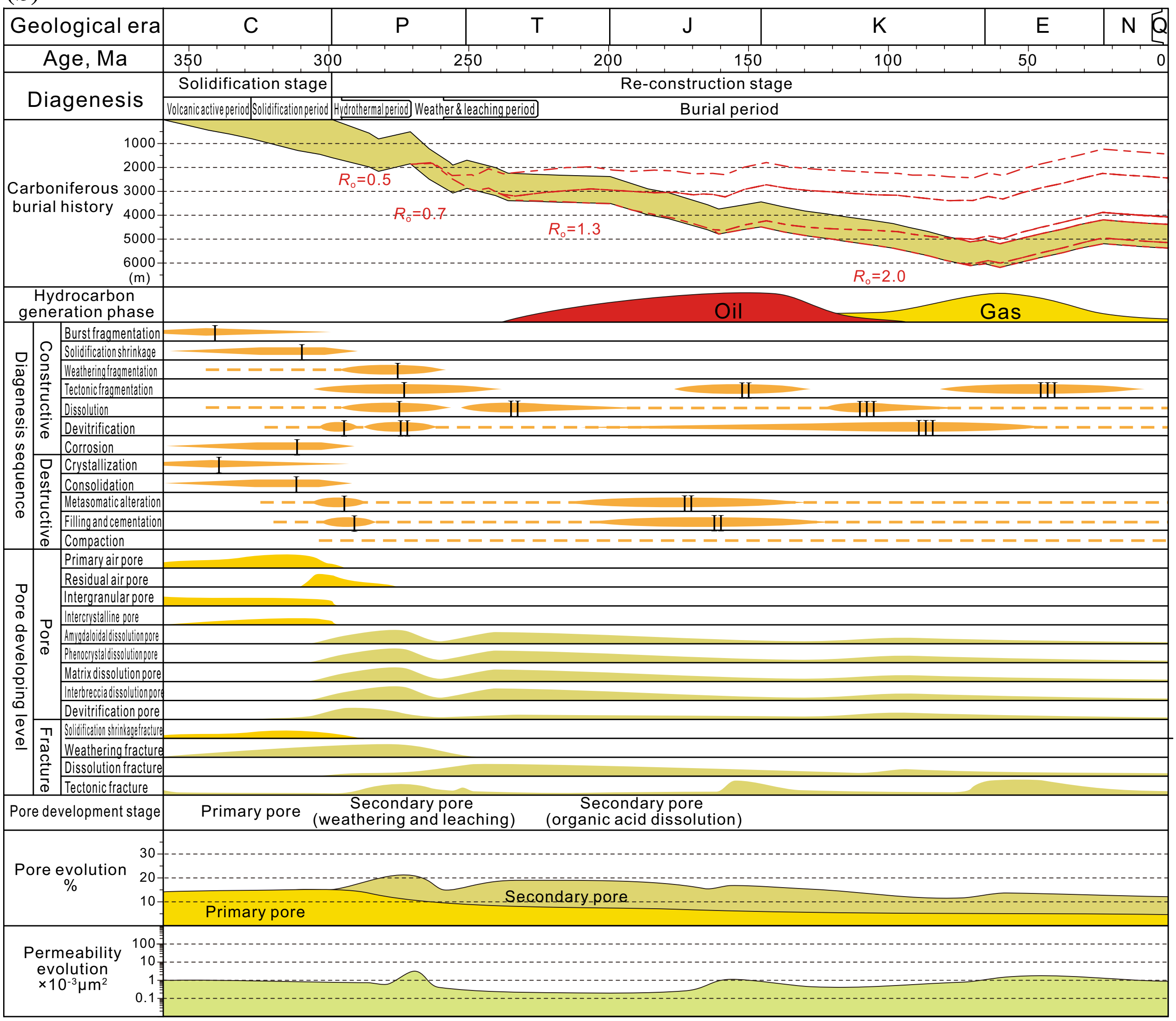

Fig. 5 continued

The eruption—weathering—burial diagenesis sequence involves the uplift and exposure of consolidated volcanic rocks at first, then prolonged weathering and leaching and reformation next, and lastly burial by sediments. Reservoir spaces are mainly secondary pores and fractures from weathering, leaching and reformation, and these form secondary volcanic reservoirs. The Carboniferous—Permian volcanic rock reservoirs in the Junggar Basin and Santanghu Basin are representatives of this type (Hou et al. 2012, 2013; Zou et al. 2012a, b).

After eruption in the Carboniferous, the Batamayineishan Formation volcanic reservoir in the Junggar Basin formed through dissolution, cooling, crystallization, welding and some other consolidation (approximately 359–320 Ma). After a short period of corrosion by hydrothermal fluids and filling of pores, volcanic rocks in this area had been uplifted and exposed till the Early Triassic (approximately 246 Ma), subject to prolonged weathering and leaching in hypergene environments, which resulted in fragmentation of rocks and secondary dissolution of minerals, and large numbers of weathering fractures and secondary pores formed (Mo and Lian 2010). After that, these formations were covered and buried by sediments. In later stages of burial, the entire region experienced several major tectonic movements, which played constructive roles in volcanic reservoir development. Generally speaking, Carboniferous volcanic rocks in the Junggar Basin experienced no less than two stages of large-scale secondary dissolution, 2–3 stages of hydrocarbon-filling events, three stages of fracture formation, one stage of siliceous cementation, two stages of carbonate cementation, two stages of chlorite cementation and three stages of anhydrite/gypsum cementation (Fig. 5b).

3.2 Origin of volcanic reservoirs

Reservoir spaces in volcanic rocks experienced extremely complicated processes of formation, development, blocking and re-construction. Different evolution processes may involve different diagenesis types, which may play dual roles of destruction and improvement to reservoirs at the same time. By a number of means, research shows that volcanic reservoirs were the product of combined effect of long-term multiple diagenesis. Complicated in formation and evolution processes, there are multiple stages of filling and dissolution. At the same time, diagenesis processes in different zones and different reservoirs also vary significantly.

(1) Development of reservoir spaces during cooling and consolidation.

Primary pores mainly form at this stage. After volcanic lava is ejected onto the surface, pores are formed by the escape of a large amount of volatile gases. Crystallization of volcanic lava resulted in the forming of small intercrystalline pores between phenocrysts, between microcrystallites, and between phenocrysts and microcrystallites. Pores among volcanic breccias were formed under volcanic eruption and explosion. Solidification of volcanic lava produced contraction fractures and other primary reservoir pores. These primary pores lay a solid foundation for the development of reservoirs at later stages. In vertical profile, lithological combinations with large amounts of lava and tuff or volcanic breccia, lava and pyroclastics can be observed, which reflect volcanic activities.

(2) Development of reservoir spaces during the epigenetic alteration stage.

Tectonic movements, weathering, leaching and fluid actions are the major geological actions affecting the development of reservoir spaces.

During periods of hydrothermal activities, alteration may occur in many rock-forming minerals. For example, augite and amphiboles may convert into chlorite; basic plagioclase may convert into kaolinite, sericite and chlorite; iddingsitization of olivine; chlorite may convert into zeolite, carbonate or other minerals; as well as carbonation and laumontitization of tuff matrix. During such alteration and conversion of minerals, hydrothermal fluids may carry large amounts of secondary minerals, e.g. chlorite, zeolite, calcite and quartz. Under suitable conditions, these minerals would crystallize, precipitate and fill up reservoir spaces, reducing volcanic reservoir capacities significantly (Yu et al. 2014). At the same time, since these minerals are mostly soluble minerals, they provide necessary materials for the later dissolution.

During weathering and leaching periods, weathering and leaching facilitate the formation of large numbers of dissolution pores in the surface and upper sections of volcanic rocks, which may connect primary reservoir spaces and enhance reservoir properties in volcanic rocks significantly. Core analysis data show that the Carboniferous basalts in the Ludong area of the Junggar Basin without weathering have an average original porosity of 7.6 %, basalts with weak weathering have an average porosity of 8.7 % and basalts with strong weathering have an average porosity of 15.3 %. Therefore, it can be seen that weathering and leaching are the major forces for the formation of secondary pores in this area.

During burial stages, volcanic rocks were covered and compacted by sedimentary rocks. Various pores and fractures generated by lava eruption, invasion, cooling, solidification, and tectonic activities and dissolution in later stages may connect pores that are originally isolated. At the same time, they may communicate with formation water in sedimentary formations to form more secondary dissolution pores and fractures. Volcanic rocks formed during early cooling, solidification and consolidation may experience prolonged dissolution by the formation of water and organic acids during their deep burial. These are the main causes for the formation of secondary reservoir spaces in volcanic rocks. Intermediate to basic basalt and andesite mainly experience re-dissolution of early fillings and alternation products. For example, partial dissolution of chlorite and calcite can be often observed in Well Shinan-3, Well Shinan-4 and Well Madong-2, but dacite may predominantly experience dissolution of amphiboles, feldspar phenocrysts and matrix. The Carboniferous dacite in the Shixi-1 well block in the Shixi Oilfield experienced the dissolution of plagioclase phenocrysts, and dissolution pores or expansion dissolution fractures can be found in the matrix. As for alkaline or strongly alkaline trachyte and phonolite, their alkalinity makes them even more sensitive to acid environments. As soon as the media environment changed from alkalinity to acidity, large amounts of alkaline feldspar phenocrysts and matrix may undergo dissolution, e.g. large amounts of dissolution pores can be observed in tephritic phonolite and trachyte andesite cores in Well Xiayan-2 and Well Shidong-8. In fact, acidic fluids can be further classified as inorganic and organic acids. They may participate in reactions individually or jointly in different areas. Areas with volcano eruption and in vicinity of major faults may be dominated by inorganic acids, whereas dissolution induced by organic acids may be stronger in areas near oil sources. In addition, occurrence of dissolution over a large area may be closely related to the development of faults. As for various minerals, especially those most affected by dissolution, such as feldspar, they may have significantly different dissolution mechanisms for organic acid dissolution and for inorganic acid dissolution.

Above research conclusions show that diagenesis is a double-edged sword for volcanic reservoirs, the matching of filling and dissolution in different diagenetic stages, together with intensities of diagenesis processes directly affect the quality of reservoir reformation at later stages.

3.3 Controlling factors for the development of volcanic reservoirs in China

Formation, preservation and reformation of reservoir spaces in volcanic rocks during the evolution process are highly complicated. Primary pores and fractures are mostly controlled by original eruption states, namely lithology of volcanic rocks. Under the same tectonic stress, the development and preservation of structural fractures are also controlled by the original eruption states. Volcanic rocks formed after volcano eruption, cooling, solidification, compaction and consolidation contain disconnected primary pores without permeability. Only after various geological transformations in later stages, they can have reservoir capacities. On the whole, volcanism, tectonic movements, weathering, leaching and fluids are key factors and geological actions for the formation and development of reservoir spaces in volcanic rocks.

Differences in diagenesis sequences of volcanic reservoirs in eastern and western China lead to the differences of reservoir types. Primary reservoir formations in volcanic rocks are represented by the Yingcheng Formation in the Songliao Basin in eastern China. Secondary weathering reservoir formations in volcanic rocks are represented by Carboniferous formations in northern Xinjiang in western China. Different factors control the development of these two types of volcanic rocks.

Volcanic rocks in the Songliao Basin experienced relatively short weathering or no weathering at all. As a result, volcanic structures are completely preserved. Volcanic rocks have relatively complete facies with reservoirs predominantly developed in eruption facies. Major controlling factors for the storage capacity of volcanic reservoirs include lithological features, rock facies, structural fractures and dissolution by acidic fluids. To be more specific, the developments of primary pores in volcanic rocks are mainly determined by lithological features and rock facies; structural fractures may enhance the permeability of volcanic rocks and serve as seepage channels for acidic fluids in later stages. Later dissolution by acidic fluids can enlarge primary pores, whereas weathering and leaching can facilitate the formation of secondary pores and fractures. Favorable facies of volcanic rocks include intrusive facies, upper subfacies of effusive facies and air-fall subfacies of eruption facies, all of which develop primary pores. In later stages of volcanic activity, acidic fluids may rise along fractures and enter pores through fractures, stimulating the formation of dissolution pores, and eventually enlarging reservoir spaces. The upper subfacies of effusive facies, air-fall subfacies of eruption facies and intrusive facies near craters below the weathering crust, which have been reformed due to acidic fluid dissolution in later stages of volcanic activities below the unconformity surface (approximately 3,600–3,800 m), are favorable facies for the development of reservoir spaces.

The residual Carboniferous formations developed over the Paleozoic folding base in the Junggar Basin. These strata experienced uplifting and denudation over a period of 30–60 Ma from the late Carboniferous to the early and middle Permian. Consequently, volcanic structures are generally incompletely preserved with weathering crusts developed. Usually, effective reservoirs with a thickness of 300 m might develop under the weathering crust (Li et al. 2007; Zhu et al. 2010a, b). The Lower Carboniferous formation is preserved in areas with severe denudation on uplifting zones, such as Kelameilishan and Dixi Uplifts. The preserved strata in ancient sags are relatively young, mostly the Upper Carboniferous formations, such as Wucaiwan Sag and Mahu Sag. From the sag center to the surrounding areas or from the structural low parts to highs, the Carboniferous formations experienced more severe denudation with newer covering formations and better reservoir properties. High landform induced by prolonged volcanic activities facilitates weathering and denudation. Consequently, the intensities of weathering, leaching, dissolution and filling reformation during volcanic rock evolution control the effectiveness of reservoirs. Palaeohighs subject to prolonged weathering and leaching commonly contain well-developed volcanic reservoirs where hydrocarbons can accumulate.

4 Hydrocarbon exploration in volcanic rocks in sedimentary basins of China

Volcanic rocks are key components of filling series for various sedimentary basins. During the early development stage of basins, volcanic rocks were not only large in volume, but also mostly associated with rapid subsiding hydrocarbon source rocks. Therefore, they are important targets in hydrocarbon exploration (Zeng et al. 2013;

Batkhishig et al. 2014). In later burial stage, volcanic rocks, less affected by burial depths than conventional sedimentary rocks, in deep parts of basins, could be better reservoirs than conventional sedimentary rocks (Feng 2008). Accordingly, they are considered as key target layers for exploration in deep basins.

Volcanic rocks are distributed extensively in China. Three packages of favorable volcanic rocks in Carboniferous—Permian, Jurassic—Cretaceous and Paleogene formations developed in existing petroliferous basins. Volcanic rocks in eastern basins are predominantly intermediate to acidic, whereas those in western parts are intermediate to basic. These volcanic rocks cover a total area of 39×10^4 km^2, including 5.0×10^4 km^2 in the Songliao Basin in eastern China, 2.0×10^4 km^2 in the Bohai Bay Basin, 6.0×10^4 km^2 in the Junggar Basin, 1.0×10^4 km^2 in the Santanghu Basin, 2.0×10^4 km^2 in the Tuha Basin, 13×10^4 km^2 in the Tarim Basin and 7.0×10^4 km^2 in the Sichuan-Tibet area.

At present, volcanic reservoirs have been found in the Songliao, Bohai Bay, Junggar, Santanghu, Halar, Erlian and some other basins, and they are still under-explored on the whole. Preliminary studies show that the total oil resources in volcanic rocks amount to (19–26) $\times 10^8$ t, and natural gas resources are 4.2×10^{12} m^3 with an oil discovery rate of 19 %–25 % and a natural gas discovery rate of 2 %. The total equivalent hydrocarbon reserves reach (52–59) $\times 10^8$ t with a discovery rate of 6 %–7 %. With abundant remaining resources and great potential for exploration, volcanic reservoirs are important replacement domain for hydrocarbon exploration.

Novel techniques should be fully utilized in future exploration of volcanic rocks, aiming at dissolution type, fracture type secondary volcanic rocks and other favorable primary reservoir formations of pyroclastic rocks (eruption facies) and lava (effusive facies) types. Based on research of deep layers in the Songliao Basin and Carboniferous formations in the Junggar Basin, two major gas-producing areas of volcanic rocks can be constructed. Exploration of volcanic rocks in the Santanghu Basin and Bohai Bay Basin should be strengthened to bring the reserve to one hundred million tons; more exploration activities should be carried out in the Carboniferous—Permian formations in the Tuha Basin, Carboniferous basins in northern Xinjiang, Permian formations in the Tarim and Sichuan Basins, Ordos and other new areas in the hope of making new breakthroughs.

Hydrocarbon-bearing layers of volcanic rocks in eastern China are dominated by Mesozoic–Cenozoic formations, which can be classified as intra-continent rift volcanic rocks formed under an extensional environment. The volcanic rock distribution is related to major faults, whereas hydrocarbon reservoir combinations are controlled by the development of faulted basins (Yang et al. 2014). Generally speaking, volcanic rocks in eastern China have identical structural environment to hydrocarbon source rocks with their distribution ranges coinciding with each other. In this way, a self-generation and self-preservation reservoir combination is formed. Due to different basin evolutions, deep layers in the Songliao Basin are mostly dominated by gas reservoirs in volcanic rocks, whereas the Bohai Bay, Erlian and Halar Basins are dominated by oil reservoirs. The distribution areas of volcanic rocks in northern Xinjiang primarily include Carboniferous—Permian formations in the Junggar, Santanghu, Tuha and some other basins, which were generated in the Xingmeng oceanic trench. Their reservoir combinations experienced significant changes due to intense basin reformation in later stages. There are not only near-source combinations, such as Ludong-Wucaiwan area in the Junggar Basin and Malang Sag in the Santanghu Basin, but also far-source reservoir combinations, such as the northwestern edges of the Junggar Basin. The distribution of hydrocarbons in these structures is predominantly controlled by unconformities and faults.

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