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Characteristics of Volcanic Reservoirs and Hydrocarbon Accumulation of Carboniferous System in Junggar Basin, China

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ABSTRACT: The Carboniferous volcanic reservoirs in Junggar Basin contain rich hydrocarbon resources, implying a great exploration potential, so that they have become a key replacement target for "three-dimensional exploration". The study on the Carboniferous volcanic reservoirs and their hydrocarbon accumulation elements is significant for clarifying the orientation for exploration. In this paper, based on 37 reserves reports and 3 200 reservoir test data, the Carboniferous volcanic reservoirs in Junggar Basin were discussed from the prospective of lithology and lithofacies, physical properties, reservoir types, main controls on hydrocarbon accumulation, and hydrocarbon accumulation patterns. It is found that the Carboniferous in the basin is mostly in the multi-island ocean-volcanic island arc structural-sedimentary environment, so it is geologically eligible for forming *in-situ* volcanic reservoirs. The volcanic rocks are: (1) mostly distributed along deep and large faults, with the lithology and lithofacies controlled by volcanic architectures; (2) dominantly lava, followed by volcaniclastic lava and volcaniclastic rock; (3) distributed in the periphery of hydrocarbon-generating sag and within the source rocks horizontally, and concentrated in the weathering crust at the top longitudinally, possibly leading to reworked weathering crust reservoir; and (4) liable to form inner reservoirs. The volcanic reservoirs can be concluded into four hydrocarbon accumulation patterns, i.e., self-generating & self-storing in paleo-uplift and vertical migration, self-generating & self-storing in paleo-uplift and lateral migration, young-generating & old-storing in fault zone and vertical migration, and young-generating & old-storing in paleo-uplift and lateral migration. Future exploration will focus on the effective source rock development and hydrocarbon supply zones and the self-generating & self-storing and young-generating & old-storing patterns. The exploration prospects are determined to be the Ludong-Wucaiwan-Baijiahai slope belt and the southern slope belt of the Shaqi uplift (self-generating & self-storing pattern) in eastern Junggar, and the fault and nasal arch zone at the northwestern margin and the nasal arch zone (deep and large structure) in the Luxi area (young-generating & old-storing pattern) in western Junggar.
KEY WORDS: Carboniferous volcanic reservoir, volcanic rock, reservoir characteristic, hydrocarbon accumulation, lithology and lithofacies, Junggar Basin.

0 INTRODUCTION

The formation and evolution of sedimentary basins are closely related to volcanism and volcanic rocks. Volcanic rocks are an important part of the filling of various sedimentary basins (Mao et al., 2015; Schutter, 2003). Oil and gas exploration shows that volcanic rocks are developed in basins such as continental rifts, continental margins, back-arc foreland and trench-arc system, and have favorable oil and gas storage conditions (Petford and Mccaffrey, 2003; Seemann and Schere, 1984; Powers, 1932). At present, volcanic reservoirs or oil-gas shows have been discovered in more than 300 basins in more than 20 countries on five continents (Sruoga and Rubinstein, 2007; Bradshaw et al., 1999; Lewis, 1932; Udden, 1915). Volcanic rock has become a new important petroleum exploration area (Wang et al., 2015; Jiang et al., 2009; Feng, 2008). However, as an important, complex and special reservoir, volcanic rocks must be effectively matched with source rocks to form reservoirs, and the accumulation conditions and main controls of volcanic rocks are more complicated, which currently lack in-depth research. The

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research of the development characteristics and distribution rules of volcanic rocks, especially the characteristics of the pore structure in volcanic structures and their formation mechanisms and distribution rules, the types and oil-bearing properties of volcanic reservoirs and the conditions of accumulation, are still at initial stage (Zou et al., 2008). Accordingly, it is urgent to deepen the research of volcanic rock reservoir lithology, lithofacies, physical properties, oil and gas reservoir types, as well as main controls on hydrocarbon accumulation and hydrocarbon accumulation patterns.

In China, volcanic reservoirs have been discovered in Songliao, Bohai Bay, Hailar, Erlian, Junggar, Santanghu, Tarim, Sichuan and other basins, with several hundred million tons cumulative proven oil reserves and several trillion cubic meters of natural gas reserves. Two large volcanic oil and gas regions in the east and west have initially formed (Chen et al., 2014; Jin et al., 2013; Zhao et al., 2009). Especially for the Carboniferous volcanic oil and gas reservoirs in the North Xinjiang in western China, it has become the most important basement/bedrock reservoirs in Junggar Basin (Cui et al., 2013; Zhang et al., 2007). The discovery of the Karamaili volcanic gasfield in the Ludong-Wucaiwan area confirms that the Carboniferous can form a set of self-generating & self-storing reservoirs, and also indicates that the Carboniferous volcanic rocks have become a key replacement target for oil and gas exploration in the basin (Zou et al., 2008). So far, 59 Carboniferous volcanic reservoirs have been discovered, with proven oil reserves of 4.2×10^8 t and proven gas reserves of 800×10^8 m^3 approximately. Only less than 20% of the strata have been proved, leaving a huge potential of resources for exploration.

Over the decades, the studies on Carboniferous have made great progress. The Carboniferous is divided into two sets of volcanic rocks (upper and lower) intercalated with a set of sedimentary rocks, presenting a "sandwich" structure (Wang X L et al., 2013; Xiao et al., 2006). The weathering crust of volcanic rocks has a total of five layers including soil layer, hydrolysis zone, dissolution zone, disintegration zone and parental rock, among which, the dissolution zone and disintegration zone have the best physical properties and are the primary pore space for weathering crust (Li et al., 2017; Wang et al., 2011). In the west, volcanic rocks are young-generating & old-storing pattern, usually forming fault block reservoirs along faults; in the east, volcanic rocks are self-generating & self-storing pattern, mostly forming lithological reservoirs along uplift zone (Mao et al., 2015; Wang et al., 2008). The main controls for hydrocarbon accumulation in volcanic rocks are volcanic architecture, weathering crust reservoir, and effective reservoir-caprock assemblage (Hou et al., 2012; He et al., 2010). As more exploration data, reservoir data and analysis/test data are available, some problems are uncovered, such as deviation in original understanding to lithology, lithofacies and physical properties of volcanic reservoirs, inadequate analysis on main controls over volcanic reservoirs, and unreasonable classification of volcanic reservoirs and hydrocarbon accumulation patterns. Therefore, it restricts further exploration of volcanic oil and gasfields in Junggar Basin. Based on 37 reserves reports and 3 200 reservoir test data in Junggar Basin, we characterized the Carboniferous reservoirs from the prospective of lithology and lithofacies, physical properties, reservoir types, main controls on hydrocarbon accumulation, and hydrocarbon accumulation patterns. According to the reservoir characteristics and hydrocarbon accumulation patterns clarified, we delineate two exploration orientations and four prospects, providing references for the operation and decision of exploration in the Carboniferous volcanic reservoirs in Junggar Basin.

1 GEOLOGICAL SETTING

The Junggar Basin is located in the south of the Paleo-Asian Ocean tectonic domain, which is an important part of the Central Asian Orogenic Belt and a part of the eastern extension of the Kazakhstan Plate (He et al., 2018; Xiao et al., 2009; Jahn et al., 2004). It is a large superimposed petroliferous basin with an area of 13.4×10^4 km^2 (Fig. 1). The Carboniferous is mostly in the multi-island oceanic crust reduction-volcanic island arc tectonic environment and volcanic-sedimentary environment, showing a general structural framework featured with island arc in the south and rift in the north (Zhao et al., 2019; Wang S F et al., 2013; Li et al., 2012). The Carboniferous in Junggar Basin is mainly composed of marine volcanic rocks, marine-continental transitional sedimentary rocks, and transitional-continental volcanic rocks (Ablimiti et al., 2019; Tang et al., 2015; Zhao et al., 2009). According to gravity and seismic data, the volcanic rocks are predicted to be 7.8×10^4 km^2 in the basin, distributing along the inherited east-western Junggar fault zone and the paleo-uplift zone of the central depression. Vertically, the Carboniferous usually presents a "three-segment" stratigraphic pattern, with volcanic rocks in the upper segment, sedimentary rocks in the middle segment, and volcanic rocks in the lower segment (Han et al., 2019; Wu et al., 2009). In western Junggar Basin, island arc-residual ocean deep-water sediments are developed, mainly in the Lower Carboniferous. It is composed of source rocks of Permian Fengcheng Formation (P_1f) and Lower Wuerhe Formation (P_2w) and Carboniferous volcanic reservoir, forming the young-generating & old-storing reservoir (Fig. 2a; Chen et al., 2016a). In eastern Junggar Basin, post-collision extensional rift (fault depression) is developed as a result of the subduction of the residual Karamaili ocean. Within the fault depression, there is the first set of transitional effective argillaceous source rocks of the Lower Carboniferous Dishuiquan Formation (C_1d) and Upper Songkaersu Formation (C_1s^b), which form a good source-reservoir assemblage with the volcanic rocks of the underlying Lower Songkaersu Formation (C_1s^a) and the overlying Batamayineishan Formation (C_2b) (Fig. 2b; Zhang et al., 2020). Hydrocarbon accumulation in volcanic rocks is closely related to the distribution of volcanic rocks and the geological elements of proximate source rocks.

According to the overall distribution of Carboniferous volcanic rocks drilled in the basin, there are six volcanic distribution zones (Chen J et al., 2020; Chang et al., 2019; Chen Z H et al., 2016b): Ke-Bai fault zone, Hong-Che fault zone, Lubei area, Shixi-Xiayan area, Ludong-Wucaiwan area, and Fudong-Shazhang-Beisantai area, which are roughly classified into three volcanic regions, i.e., western Junggar, northern Junggar, and eastern Junggar. Since commercial discovery has been made only in the east (eastern uplift), north (Luliang uplift), and west (fault zone at the northwestern margin) of the basin, and the geological conditions in northern Junggar are similar to those in the

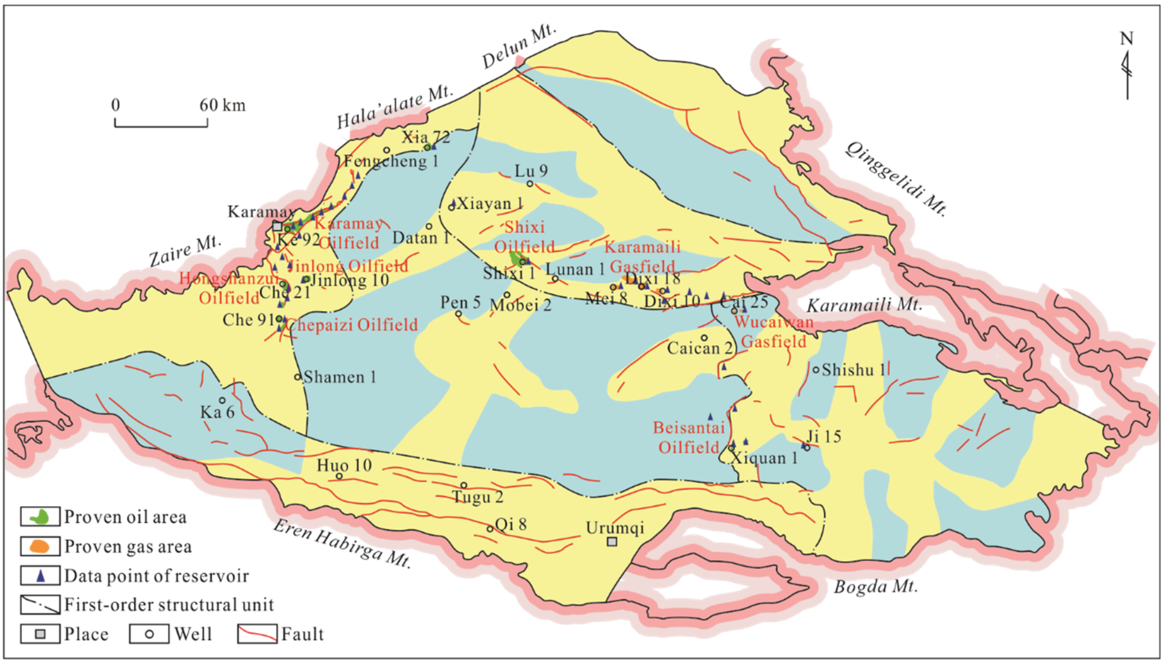

Figure 1. Oil and gas exploration results of Carboniferous volcanic rocks in Junggar Basin (modified after 2019 Exploration and Deployment Map of Xinjiang Oilfield). Mt. Mountain.

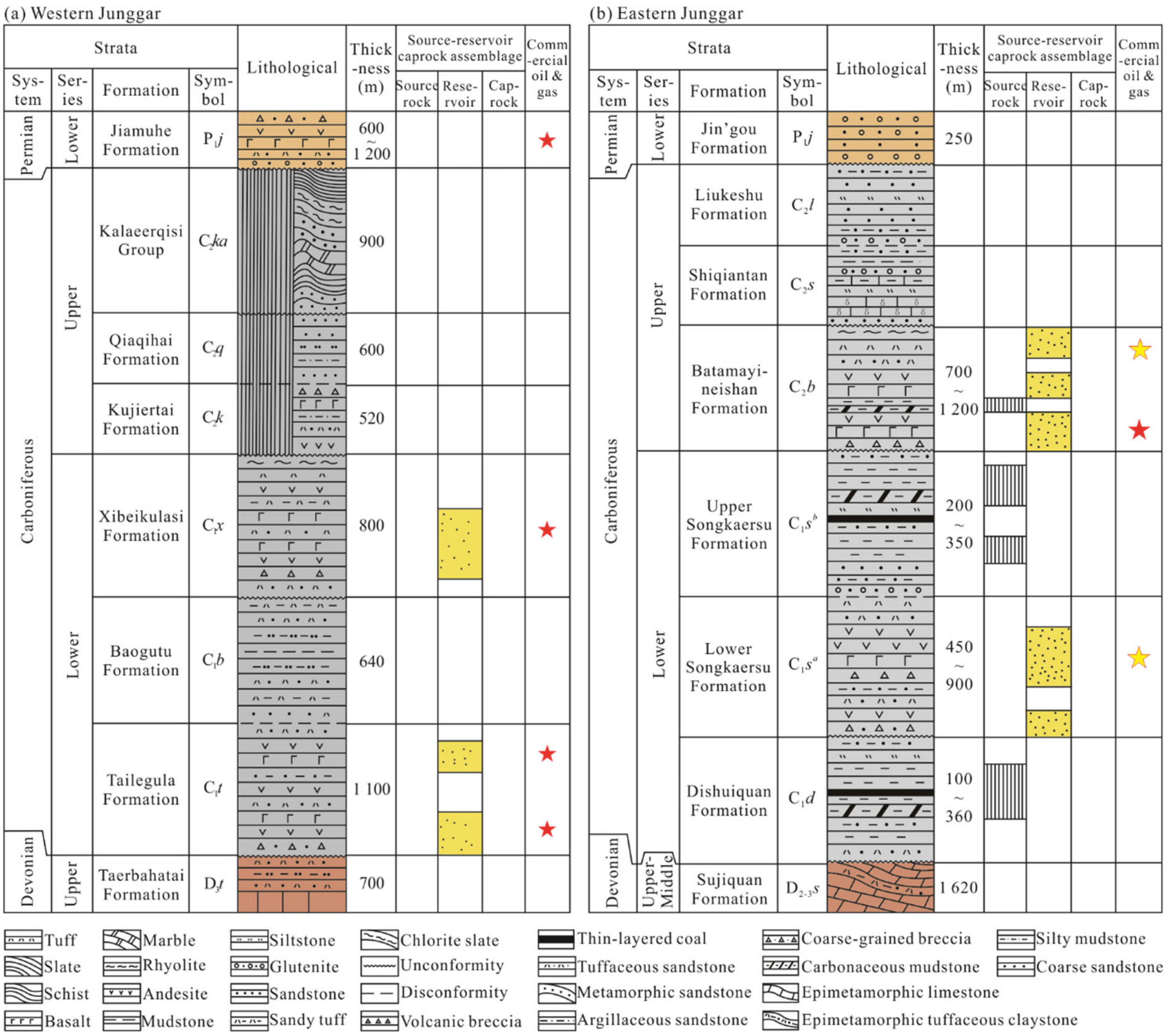

Figure 2. Stratigraphic column of Carboniferous in Junggar Basin.

northeastern margin of the basin, the reservoir sequence, accumulation sequence and hydrocarbon accumulation patterns of volcanic rocks can be analyzed based on the comparison between eastern Junggar and western Junggar (Fig. 2).

2 CHARACTERISTICS OF CARBONIFEROUS VOLCANIC RESERVOIR

2.1 Lithology and Lithofacies

According to the classification of Zhu et al. (2010), we rearranged the lithofacies of volcanic rocks in Junggar Basin based on rock type, lithology, texture, structure and occurrence. By the occurrence and depth of volcanic rocks, the area from the near-crater zone to the far-crater zone is divided into volcanic conduit facies, explosive facies, effusive facies and volcanic sedimentary facies (Table 1), so that the occurrence of volcanic rocks is highlighted, thereby providing basis for the theory of facies, reservoir, and physical properties controlled by volcanic architectures.

2.2 Pore Space and Physical Properties

2.2.1 Pore space

With reference to the classification of pore space by Wang et al. (2007), and based on the data of 37 reserves reports and the 3 200 reservoir test data, we divide the pore space of volcanic reservoirs in the basin into three types: primary pores, secondary pores, and microfractures (Table 2). The primary pores are subdivided into primary vesicle, residual vesicle, intergranular (inter-gravel) pore, and intercrystalline/intracrystalline pore, the secondary pores are subdivided into phenocryst dissolved pore, amygdaloidal dissolved pore, intra-matrix dissolved pore, and inter-breccia dissolved pore, and the microfractures are subdivided into primary condensing shrinkage fracture, structural fracture, weathering fracture, and dissolved fracture (Fig. 3).

Existence of primary pores is fundamental for the formation of effective volcanic reservoirs, but the primary pores are mostly filled or dissolved to different extents during the subsequent burial evolution. Obviously, the late alteration of the Carboniferous volcanic rock is pivotally important to the formation of reservoir (Zhang et al., 2014). According to the type of pore space, the volcanic rock is a dual-media reservoir with typical dissolved pores and microfractures (Li et al., 2010; Lin et al., 2009). The Carboniferous reworked weathering crust volcanic reservoirs generally demonstrate the pore space in three combinations: structural fracture+dissolved fracture+dissolved pore, primary vesicle+structural fracture+dissolved fracture+dissolved pore, and intercrystalline pore+primary pore+structural fracture+dissolved pore. The last combination is mainly observed in volcaniclastic rocks. Various types of pore spaces can be found in the Lower Carboniferous volcanic reservoirs in east-western Junggar. Primary vesicles and dissolved pores exist in the near-crater explosive facies and explosive facies belts, implying the possibility of high-quality reservoirs. Secondary pores are mostly developed in far-crater facies belts, where the development degree of weathering and structural fractures determines the alteration degree and storage capacity of reservoir. The reservoirs are dominantly fracture-pore type (interconnected fractures, microfractures and pores) and fracture type (microfractures and fractures) (Zhang et al., 2018).

Table 1 Lithofacies and characteristics of Carboniferous volcanic rocks in Junggar Basin (modified after Zhu et al., 2010)

Facies	Subfacies	Depth	Major rock types	Typical lithologies	Texture	Structure	Occurrence	Remarks
Effusive	Upper	Surface	Lava	Basalt, basaltic andesite, andesite, rhyolite	Interlaced, intergranular, and intersertal	Fumarolic, amygdaloidal, lithophysa, rhyolitic	Lava flow, lava sheet; rope-like, dreg-like, columnar, pillow-like lavas	Products of volcanic effusion and overflow
	Middle							
	Lower							
Explosive	Near-crater	Surface	Volcaniclastic rock	Tuffaceous breccia, breccia, agglomerate, welded tuff	Volcaniclastic	Massive	Fallout, volcaniclastic flow, near-crater spattering	Products of volcanic explosion
	Far-crater			Tuff	Tuffaceous	Massive	Floating, far-crater spattering	
Volcanic conduit	Subvolcanic	Subsurface	Intrusive rocks	Granite porphyry, diorite-porphyritic, dolerite	Porphyritic texture	Massive	Near surface, super-shallow, shallow strata	Produced at the volcanic architecture and its periphery
Volcanic sedimentary	Continental	Surface	Sedimentary volcaniclastic rock, volcaniclastic sedimentary rock, sedimentary rocks, etc.	Lacustrine mudstone, marine mudstone, tuffaceous sandstone, tuffaceous glutenite, sedimentary tuff	Rounded agglomerate, volcaniclastic/terrigenous sedimentary texture	Layered	Fluvial-lacustrine sediments, marine sediments; layered and lenticular sediments	Products in the volcanic explosive intermittence and in the low ebb
	Marine							

Table 2 Types and characteristics of pore space of Carboniferous volcanic reservoirs in Junggar Basin

	Type	Formation mechanism	Characteristics	Lithologies
Primary pores	Primary vesicle	Generated by gas expansion and overflow in diagenesis	Frequently distributed at the top and bottom of rock flow layer, with varying sizes and morphologies	Volcanic breccia, lava
	Residual vesicle	Residual pores under the condition that secondary minerals don't fully fill the vesicle	Semi-filled pores	Basalt, volcanic breccia
	Intergranular (inter-gravel) pore	Residual pores formed by the compaction of void space between clastic particles	Frequently observed in volcaniclastic rocks	Volcanic breccia, agglomerate, volcanic sedimentary rocks
	Intercrystal/ intracrystal pore	Pores in the framework of phenocryst minerals such as pyroxene and plagioclase with cleavages, which are intracrystal pores in nature	Frequently distributed in the middle of rock flow layer, with small void space	Lava, volcaniclastic rock
Secondary pores	Phenocryst dissolved pore	Pores formed by the dissolution of phenocryst in the flow process (usually) along the cleavage fractures	Irregular pore morphology, frequently in estuary distribution, with intracrystal pore in dominance	Andesite, rhyolite
	Amygdaloidal dissolved pore	Formed by the metasomatic dissolution of fillings in the vesicles	Irregular pore morphology, with poor connectivity	Basalt, lava
	Intra-matrix dissolved pore	Formed by devitrification of vitric in the matrix or dissolution of micro-crystal feldspar	Tiny pores, with dissolved pores in dominance, certain connectivity	Welded tuff, tuff, dolerite,
	Inter-breccia pore	Formed in epigenesis such as weathering, leaching, and dissolution	Developed along the fractures, clastic rock belts, and structural highs	Basalt, andesite, breccia
Microfractures	Primary condensing shrinkage fracture	Shrinkage microfractures formed in the magma condensation and crystallization	Columnar joint, showing opening mode and sheet fracturing without evident displacement	Volcanic breccia, andesite, trachyte
	Structural fracture	Microfractures formed in volcanic rocks under the action of tectonic stress	Developed near the fault, relatively flat and straight, mostly high-angle fractures	Basalt, andesite
	Weathering fracture	Frequently intersected with dissolved pores, fractures and structural fractures, which cut the rocks into various fragments	Connected with dissolved pores, fractures and vugs, and with structural fractures	Volcaniclastic rock, volcanic breccia
	Dissolved fracture	Formed by leaching and dissolution		Amygdaloidal andesite, volcanic breccia

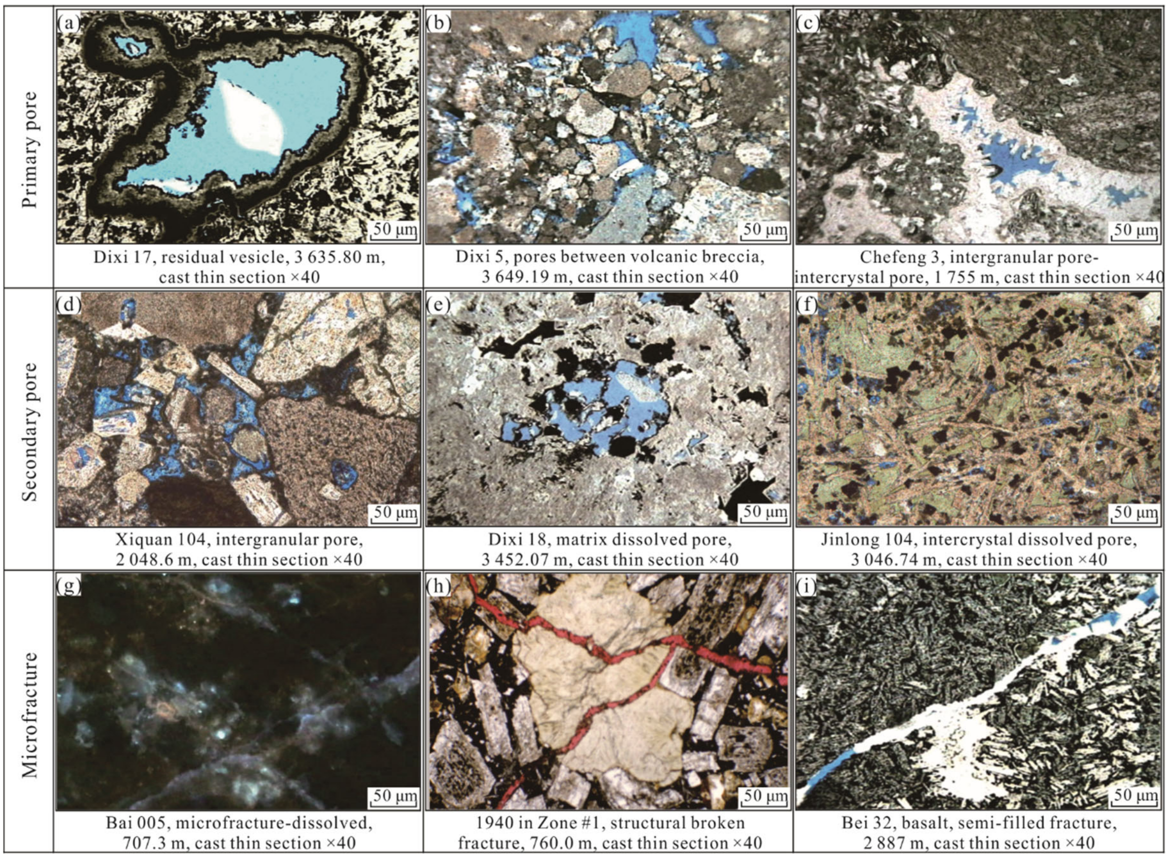

Figure 3. Types of pore space in the Carboniferous volcanic reservoirs in Junggar Basin.

2.2.2 Physical properties

The Carboniferous volcanic reservoirs in the basin are diverse and tight in lithology, and the lithology, lithofacies and pore space determine their strong heterogeneity, exclusively being homogeneous reservoirs with medium-low porosity and low-extra-low permeability (Jin et al., 2018; Song et al., 2016). The physical properties are extremely variable for different lithologies and lithofacies in horizontal and vertical directions. As a kind of *in-situ* accumulation, volcanic reservoirs are widespread very differently from region to region (Wang et al., 2012). Generally, the volcanic reservoirs show better physical properties in the Upper Carboniferous than in the Lower Carboniferous, in volcaniclastic rocks than in lava, and in intermediate acidic lava than intermediate basic lava (Zhu et al., 2012). The Lower Carboniferous is dominant at the northwestern margin of the basin, while the Upper Carboniferous is dominant in eastern Junggar (Wu et al., 2011).

According to 37 reserves reports and 3 200 reservoir test data, the lithofacies include explosive facies→effusive facies→near-crater sedimentary facies→volcanic conduit facies→sub-volcanic facies→far-crater sedimentary facies, in an ascending order of distance to the crater (Fig. 4a). By lithologies, the volcanic reservoirs with the best physical properties are welded (vesicle) basalt, amygdaloidal (vesicle) andesite, volcanic breccia, welded (vesicle) tuff, rhyolitic dacite, amygdaloidal basaltic andesite, and vesicle basaltic andesite, followed by agglomerate, andesite basalt, basaltic andesite, dolerite, rhyolitic breccia, rhyolite, and andesite; the lithofacies with the worst physical properties are tight basalt, tight andesite, tuff, dolerite, and sandy tuff (Fig. 4b). For the Carboniferous volcanic rocks in the Di'nan uplift zone in the eastern segment of the Luliang uplift, the rocks of explosive facies include agglomerates, volcanic breccia, tuff, breccia-bearing tuff, tuffaceous volcanic breccia and rhyolitic breccia (with a porosity of 8.91%); the rocks of effusive facies include amygdaloidal andesite, rhyolitic dacite, amygdaloidal basaltic andesite, basaltic andesite, and andesite (with a high porosity of 7.12%); the rock of volcanic conduit facies is andesitic tuff lava (with a porosity of 6.07%); the rocks of volcanic sedimentary facies include crystal debris tuff (with a porosity of 7.33%) and sedimentary tuff (with a porosity of 5.45%).

3 TYPES OF VOLCANIC RESERVOIRS

Scholars have presented three main different division schemes of volcanic reservoirs types in Junggar Basin. He et al. (2010) divided volcanic reservoirs into two types according to Upper and Lower Carboniferous and lithology: Upper and Lower Carboniferous volcanic rocks and glutenite, which were divided into 9 subtypes by trap types. Zou et al. (2011) divided volcanic reservoirs into three types based on the locations of reservoirs and source rocks: intra-source, above-source, and side-source, which were divided into three subtypes, i.e., stratified volcanic rocks, quasi-stratified volcanic cones, and unconformable comb, according to the volcanic reservoir morphology. Tang et al. (2015) divided volcanic reservoirs into two patterns according to the oil and gas sources, i.e., self-generating & self-storing and young-generating & old-storing, and into weathering crust and inner reservoirs based on the location of reservoir in the volcanic rocks. These three division schemes respectively

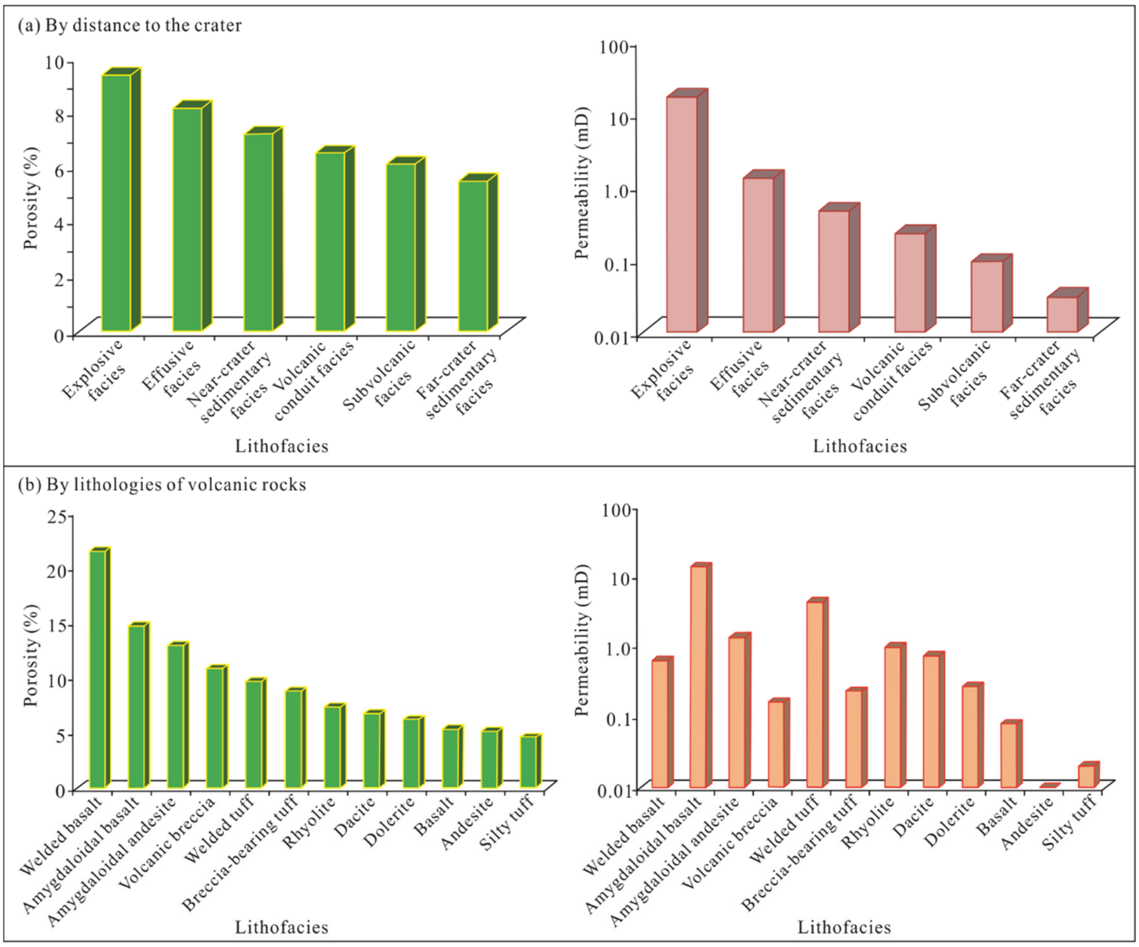

Figure 4. Histograms of physical properties of Carboniferous volcanic reservoirs with different lithologies in Junggar Basin.

focus on lithology and trap types, source-reservoir relationship, and reservoir characteristics. In fact, volcanic reservoirs in Junggar Basin were often formed near source. Effective source rocks in different regions controlled the distribution of volcanic reservoirs, and together with the characteristics of reservoirs and traps, determined the type of volcanic reservoirs.

Therefore, based on the latest exploration results, comprehensively considering the three elements of source rocks, reservoir types and trap types, and the above three previous division schemes, the Carboniferous volcanic reservoirs in Junggar Basin are divided into 10 types. First, according to the distribution range of the main source rocks and the relationship between source and reservoir, volcanic reservoirs are divided into two categories: self-generating & self-storing pattern and young-generating & old-storing pattern. This classification focuses more on source types and reservoir occurrence than conventional classification. The former type is characterized by hydrocarbon accumulation near the Carboniferous source rocks, which can be found in the Ludong-eastern Junggar area. The latter type is formed near the Permian source rocks and distributed in the Luxi-northwestern margin of the Junggar Basin. Second, on the basis of clarifying the main source of oil and gas, the reservoirs are subdivided by the types of reservoir and trap. Among them, self-generating & self-storing pattern can be subdivided into 6 types: weathering crust-stratigraphic-lithological type, anticline type, anticline-lithological type, fault-stratigraphic type, stratified-buried hill type and inner buried-hill type. Young-generating & old-storing pattern can be subdivided into 4 types: fault block type, fault anticline-buried hill type, fault anticline type and weathering crust-buried hill type (Table S1 and Fig. 5). This division scheme not only comprehensively considers the type and matching relationship of source rocks, reservoirs and traps, but also conforms to the characteristics of different types of volcanic reservoirs formed under the control of different main source rocks in different areas of Junggar Basin, and corresponds to the volcanic reservoirs discovered in various oilfields in the basin, which ensures that it has better applicability in exploration practice.

3.1 Self-Generating & Self-Storing Pattern

Self-generating & self-storing pattern of conventional reservoirs is an intra-source pattern, namely, source rocks and reservoir rocks are in the same interval. Unlikely, the self-generating & self-storing pattern of volcanic reservoirs does not refer to the volcanic rock itself, which can't act as source rock but only as *in-situ* accumulation. For purpose of differentiation, the self-generating & self-storing pattern of volcanic reservoirs is scaled to the entire strata, thereby distinguishing it from the concept of "young-generating & old-storing" which crosses strata.

3.1.1 Weathering crust-stratigraphic-lithological type

In this type of oil and gas reservoirs, volcanic rocks are exposed as buried hills and are weathered and denudated to form weathering crust reservoirs. Stratigraphic boundaries, lithological bodies and faults jointly constitute traps. For example, the volcanic reservoirs in the Well Dixi 18 area of the Di'nan uplift zone in the Ludong area are granite bedrock accumulations of the Carboniferous Batamayineishan Formation intrusions, and they were formed under the control of lithology and stratigraphic pinchout, as well as the control of faults (Fig. 5a).

3.1.2 Anticline type

The top and periphery of this type of reservoirs are covered by caprocks, showing the morphology of an intact anticline. For example, the oil reservoir in the Xidi No. 1 anticline in the Beisantai uplift is a drape anticline structure developed on the setting of Carboniferous bedrock uplift without the development of faults. It is the eruption from a single crater, with its lithology controlled by volcanic texture (Fig. 5b).

3.1.3 Anticline-lithological type

Anticline-lithological reservoirs are based on lithological traps (e.g., volcanic rock bodies and volcaniclastic sandstone bodies), and developed in an anticline shape under the setting of uplift structure. Horizontally, the oil- and gas-bearing boundaries are lithological boundaries. For example, the Carboniferous volcanic gas reservoirs in the Well Dixi 10 area of the Di'nan uplift are controlled jointly by anticlinal traps and volcanic accumulations (Fig. 5c).

3.1.4 Fault-stratigraphic type

Strata and stratified volcanic lithologic bodies jointly constitute a trap, forming a fault-stratigraphic oil and gas reservoir. For example, in the southern belt of the second-step uplift in the Di'nan uplift, the Carboniferous volcanic reservoirs in the Well Mei 6–Mei 8 area are distributed in layers; the gas reservoirs are not only controlled by faults, but also influenced by stratigraphic truncation and pinching-out and lithology in the east-west direction (Fig. 5d).

3.1.5 Stratified-buried hill type

The type is mostly developed on inherited paleo-uplift or paleo-structure. The Carboniferous volcanic reservoirs are distributed in stratified manner along the top of buried hill, with overlying mudstone as seal at the top and possibly lithological boundary in lateral direction. For example, the Carboniferous volcanic reservoirs in the Well Xiquan 1–Xiquan 10 area of the Beisantai uplift are stratified under the setting of buried hill (Fig. 5e).

3.1.6 Inner buried-hill type

Under the setting of the ancient anticline and monocline structures, hydrocarbons accumulate effectively again inside the buried-hill reservoir formed beneath the weathering crust at the top of volcanic reservoirs. This type of reservoir is often complementary to the weathering crust type and controlled by faults and unconformity, with overlying mudstone as seal at the top and possibly stratigraphic-lithological boundary in lateral direction (Fig. 5f).

3.2 Young-Generating & Old-Storing Pattern

3.2.1 Fault block type

This type is mainly found in fault zones, especially in the vicinity of fault zone or inherited uplift zone. The reservoir is surrounded by fault which is the basic element for sealing oil and gas. For example, the Carboniferous volcanic oil reservoir in the Well Jinlong 10 area of the Zhongguai uplift at the northwestern margin of the basin is sealed by fault, generally representing as a fault block reservoir (Fig. 5g).

3.2.2 Fault anticline-buried hill type

In this type of reservoirs, the volcanic body constitutes a buried hill, which is in the form of a fault anticline, covered by mudstones of the Permian, Triassic, and Jurassic. For example, in the Carboniferous volcanic oil reservoir in Shixi, the fault anticline is denudated into residual buried hill, with the upper part sealed by the Middle–Upper Triassic mudstones. The present-day oil reservoir contains bitumen left after the destruction of early reservoir, indicating that it was formed by the charging of mature and high-mature hydrocarbons in late stage (Fig. 5h).

3.2.3 Fault anticline type

This type generally represents as an anticlinal structure, with one wing mostly cut, forming a fault anticline. Fault is an element for sealing oil and gas. This type of reservoir is common in zones #4, #6, #7 and #9 of the hanging wall of the Ke-Bai fault zone at the northwestern margin and in the hanging wall of the Hong-Che fault zone. For example, in the Well Che 210 area of the Chepaizi fault zone, multiple fault anticline reservoirs exist as a result of the intersection of volcanic rock bodies at the front of the nappe zone (Fig. 5i).

3.2.4 Weathering crust-buried hill type

This type is mainly developed in the hanging wall of fault zone. The nappe fault pushes the volcanic bodes up as a whole, forming the palaeomorphology of buried hill. The weathering crust reservoir is formed due to strong weathering and leaching along the unconformity. Oil and gas supplied by the footwall migrate vertically along faults and then along the unconformity surface to accumulate finally. The oil reservoir is mainly controlled by fault, unconformity and lithology (Fig. 5j).

4 HYDROCARBON ACCUMULATION IN VOLCANIC ROCKS: MAIN CONTROLS AND PATTERNS

4.1 Main Controls on Hydrocarbon Accumulation

In the Carboniferous volcanic rocks, hydrocarbons accumulate near the effective source rocks. Also, the thermal evolution degree of the source rocks determines the accumulation pattern: self-generating & self-storing, or young-generating & old-storing. So, hydrocarbon accumulation occurs in different structures in different regions (Kuang et al., 2007). In western Junggar, hydrocarbons mainly accumulated along fault zones; in eastern Junggar, hydrocarbons mainly accumulated along inherited uplift zones. Structural patterns determine the hydrocarbon accumulation style and pattern.

In western Junggar, there are mainly young-generating & old-storing reservoirs around the effective source rocks in the Middle–Lower Permian of the footwall of the fault zone at the northwestern margin. In eastern Junggar, there are mainly self-generating & self-storing reservoirs around the effective source rocks in the Carboniferous (Fig. 6). Hydrocarbon accumulation is mainly controlled by oil/gas-source fault+lithology (lithofacies)+ unconformity in the tectonic setting.

4.2 Patterns of Hydrocarbon Accumulation

According to the hydrocarbon source, thermal evolution of

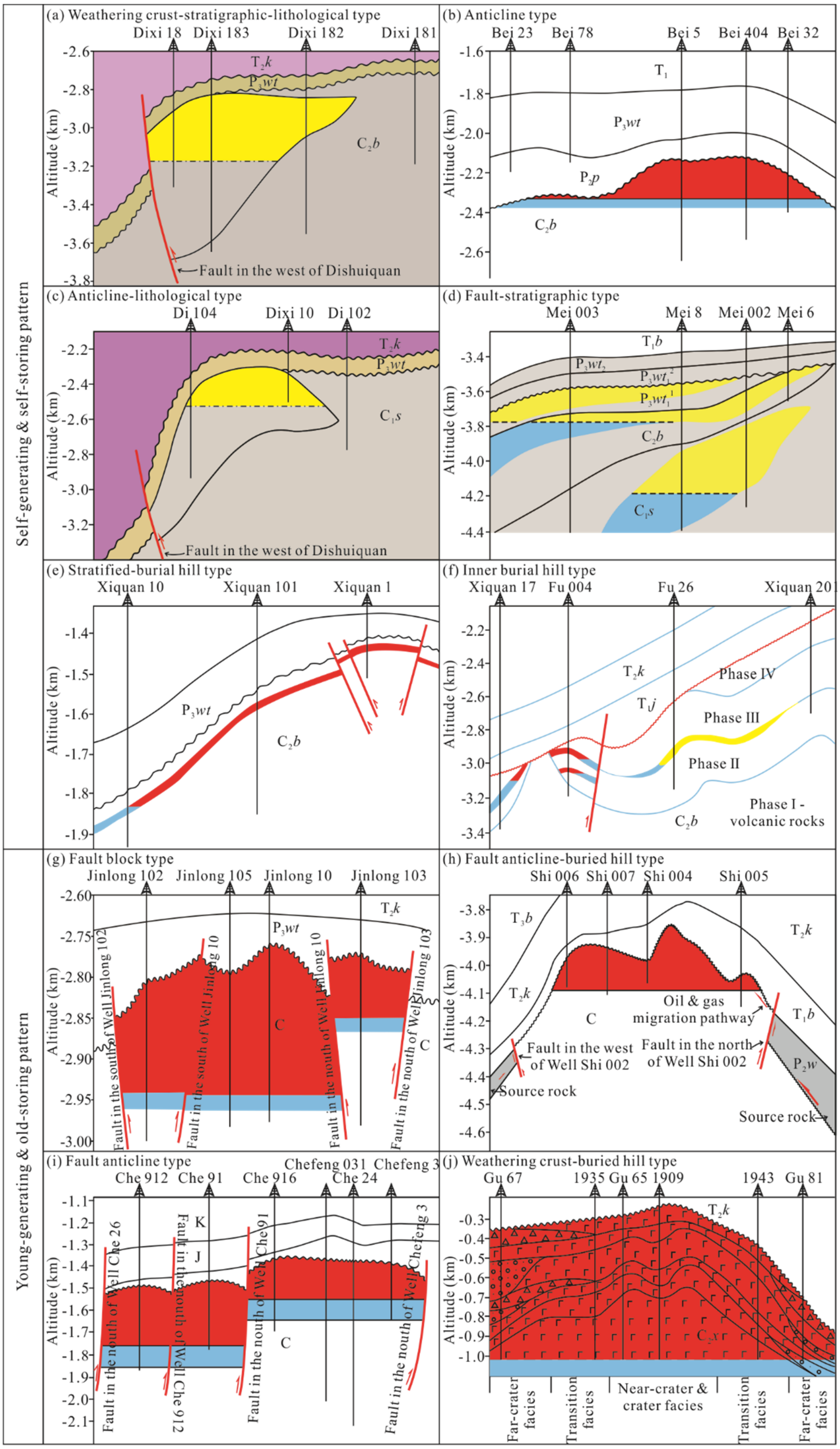

Figure 5. Classification of Carboniferous volcanic reservoirs in Junggar Basin.

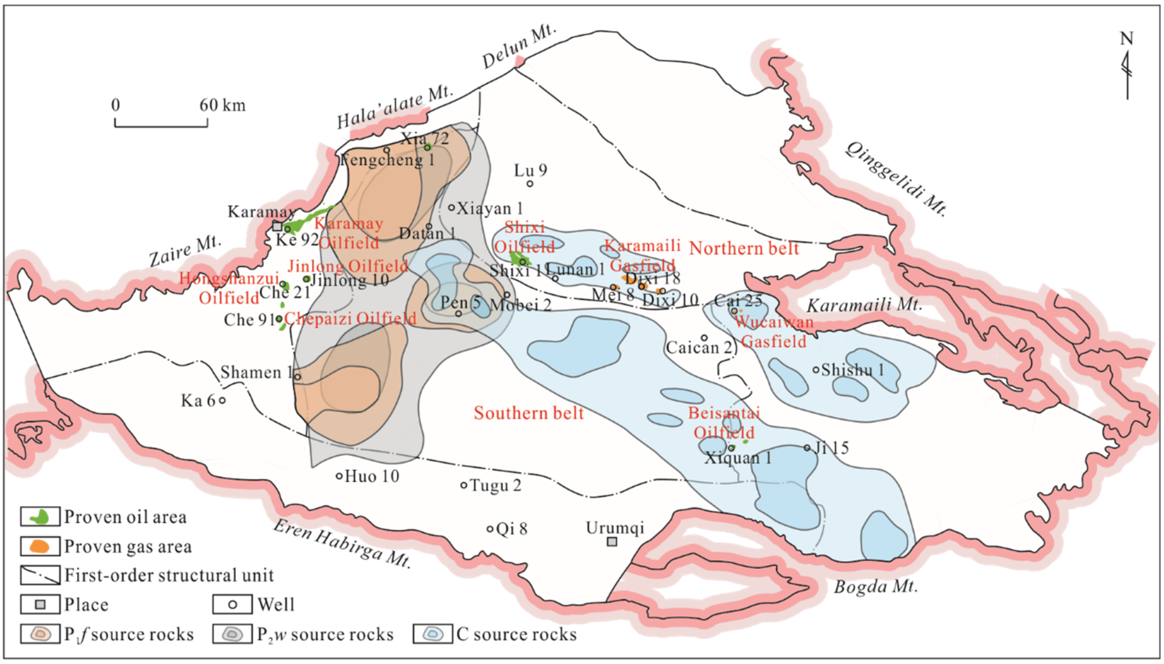

Figure 6. Distribution of source rocks closely related to hydrocarbon accumulation in the Carboniferous volcanic rocks in Junggar Basin (the base map is modified after the internal data of Xinjiang Oilfield).

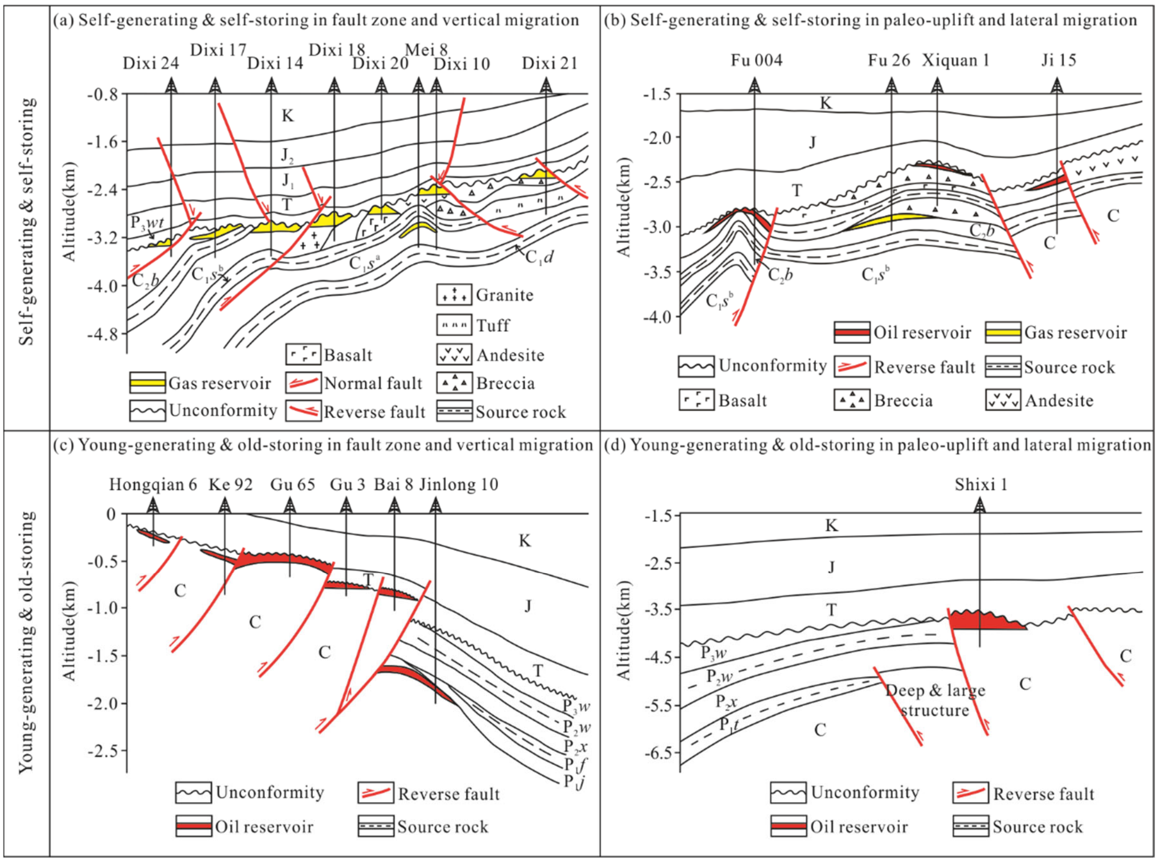

Figure 7. Hydrocarbon accumulation patterns of the Carboniferous volcanic reservoirs in Junggar Basin.

effective source rocks, accumulation structural zone, and distribution of source-reservoir-caprock assemblage, the Carboniferous volcanic reservoirs in Junggar Basin are believed to derive from four hydrocarbon accumulation patterns, i.e., self-generating & self-storing in paleo-uplift and vertical migration, self-generating & self-storing in paleo-uplift and lateral migration, young-generating & old-storing in fault zone and vertical migration, and young-generating & old-storing in paleo-uplift and lateral migration (Fig. 7).

4.2.1 Self-generating & self-storing in paleo-uplift and vertical migration

This pattern is mainly found in the Carboniferous volcanic rocks in the Ludong (Di'nan and Dibei uplifts)-Wucaiwan sag-Shishugou sag-Baijiahai uplift area, where volcanic gas reservoirs are developed in inherited paleo-uplift, nasal arch zone, and structural highs of the slope zone. Hydrocarbons are accumulated near the source rocks, mainly around the argillaceous source rocks of the Dishuiquan Formation and the Upper Songkaersu Formation. The gas generation intensity of source rocks determines the range of accumulation. Mostly, under the structural setting of uplift zone, the weathering crust reworked volcanic reservoirs formed along the unconformity evolve to the pattern of self-generating & self-storing and near-source vertical migration, including weathering crust-stratigraphic-lithological type (Well Dixi 18 area), anticline-lithological type (Well Dixi 10 area), fault-stratigraphic type (wells Mei 6–Mei 8 area), and inner buried-hill type (Fig. 7a). This pattern is characterized by near-source, inherited paleo-uplift, weathering crust reservoir, Upper Permian mudstone as the seal, and self-generating & self-storing in the Carboniferous strata. Main controls on hydrocarbon accumulation are paleo-uplift+lithofacies+weathering crust+mudstone caprock.

4.2.2 Self-generating & self-storing in paleo-uplift and lateral migration

This pattern is mainly found in the Carboniferous volcanic rocks in the Fudong slope-Sha'nan nasal arch-Beisantai uplift-Jimusaer sag-Gucheng sag area, where volcanic gas reservoirs are developed in inherited paleo-uplift, nasal arch zone and the structural highs of the slope zone. In the Late Triassic–Early Jurassic, the source rocks entered the oil generation peak and the oil and gas was accumulated in the paleo-uplift zone and nasal arch zone by lateral migration along unconformity. In the later period, they were further reworked with structural alterations and fault damage, and the scale of the reservoir was shrunk by dissipation, representing as the anticline type (Well Bei 32 area), fault-lithological type (Well Ji 15 area), stratified-buried hill type (Well Xiquan 1), and inner buried-hill type (Well Fu 26 area), under the setting of paleo-structure, paleo-nasal arch and paleo-slope (Fig. 7b). This pattern is characterized by near-source, unconformity, paleo-uplift, stratified lithology, overlying mudstone as the seal, and self-generating & self-storing in the Carboniferous strata. Main controls on hydrocarbon accumulation are unconformity+paleo-uplift+lithofacies+mudstone caprock.

4.2.3 Young-generating & old-storing in fault zone and vertical migration

This pattern is mainly found in the Carboniferous volcanic rocks in the fault zone at the northwestern margin, where the volcanic oil reservoirs are developed on the hanging wall of the major fault and structural highs of the Zhongguai uplift. In the Ke-Bai fault zone at the northwestern margin, the fault block, fault block-lithological, and fault-sealing traps are frequently developed, forming the pattern of young-generating & old-storing in fault zone and vertical migration. At the end of Triassic, oil generated from the Fengcheng Formation source rocks migrated vertically along the fault zone and then along the paleo-uplift and the unconformities at the bottoms of Triassic, Jurassic and Cretaceous in the northwestward direction, in an ascending "fault step" manner, and finally accumulated in the Carboniferous volcanic rocks to form volcanic reservoirs in zones #1–2, zones #6–7–9 and the Jinlong area. In the Hong-Che fault zone, in Late Cretaceous, oil generated from the Lower Wuerhe Formation source rocks migrated vertically along the fault zone, and then along the unconformities at the bottoms of Triassic and Jurassic in the westward direction, in an ascending zigzag manner, and finally accumulated in the Carboniferous volcanic rocks to form the Carboniferous volcanic reservoirs in Hongshanzui, Che 21, and Chefeng 3 (Fig. 7c). This pattern is characterized by fault zone, oil source fault, unconformity, lithology, and young-generating & old-storing in the Carboniferous crossing strata. Main controls on hydrocarbon accumulation are fault sealing+unconformity+lithology.

4.2.4 Young-generating & old-storing in paleo-uplift and lateral migration

This pattern is mainly found in the Carboniferous volcanic rocks in the Luxi (Shixi uplift, Sannan sag, Xiayan uplift, Sangequan uplift, and Yingxi sag in the western section of the Luliang uplift)-Dabasong uplift-Mobei uplift-Mosuowan uplift area, where the Carboniferous volcanic oil reservoirs are developed in the uplift zone and the structural highs of the nasal arch zone. Hydrocarbons accumulated after lateral migration from the argillaceous source rocks in the Lower Permian Fengcheng Formation and the Middle Permian Lower Wuerhe Formation in the adjacent sag-the West Well Pen 1 sag. In the Late Yanshanian, the Lower Wuerhe Formation source rocks entered the oil window, forming a huge supplement to oil source. Oil and gas migrated along the dominant pathways to the paleo-uplift, paleo-nasal arch and structural highs of the slope zone, giving rise to the anticline, stratigraphic-lithological, fault anticline, and buried-hill type volcanic reservoirs (Fig. 7d). This pattern is characterized by inherited paleo-uplift, unconformity, favorable lithofacies, overlying mudstones, and young-generating & old-storing in the Carboniferous crossing strata. Main controls on hydrocarbon accumulation are paleo-uplift+unconformity+lithofacies+mudstone caprock.

5 EXPLORATION PROSPECTS

Hydrocarbon accumulation in the Carboniferous volcanic rocks is controlled by the factors such as effective source rock distribution, favorable reservoirs, faults and lateral migration systems, effective reservoir-caprock assemblage, and effective preservation conditions. The reservoirs are distributed near the center of source rocks, with the oil and gas productivity controlled by the distribution of high-quality reservoir, and the oil and gas enrichment controlled by faults. Lithology of strata inside the Carboniferous and overlying strata and fault sealing are critical for oil and gas preservation. Considering the distribution and structural features of Carboniferous volcanic rocks, effective source rock distribution, reservoir-caprock assemblage, main controls on hydrocarbon accumulation, hydrocarbon accumulation patterns, and recent progress in oil and gas exploration, it is clarified that the exploration of the Carboniferous volcanic rocks in the basin must be based upon the characteristics of near-source accumulation.

The exploration targets: (1) the self-generating & self-storing type reservoirs in the fault depressions of the southern belt and northern belt of the Carboniferous effective source rocks in eastern Junggar (exploration operations have achieved favorable progress in the structural highs of the structural highs of the uplift zone in the early stage, and will extend to the nasal arch zone, slope zone, and inner rock bodies); and (2) the fault zone and uplift zone at the northwestern margin, with hydrocarbons supplied by the Permian source rocks in the Mahu-Shawan-West Well Pen 1 sag area (exploration operations have achieved favorable progress in the structural highs in the front fault block, nappe and uplift of the fault zone, and will be carried out further in the fault zone and extend to the structural highs in the overlapping zone, uplift zone, and nasal arch zone in the fault zone.

The exploration prospects include (Fig. 8): (1) the Ludong-Wucaiwan-Baijiahai slope belt (self-generating & self-storing pattern); (2) the southern slope belt of the Shaqi uplift (self-generating & self-storing pattern); (3) the fault and nasal arch zone at the northwestern margin (young-generating & old-storing pattern); and (4) the nasal arch zone in the Luxi area (young-generating & old-storing pattern).

6 CONCLUSIONS

(1) According to rock type, lithology, texture, structure and occurrence, the area from the near-crater zone to the far-crater zone is divided into volcanic conduit facies, explosive facies, effusive facies and volcanic sedimentary facies, so that the occurrence of volcanic rocks is highlighted, thereby providing basis for the theory of facies, reservoir, and physical properties controlled by volcanic architectures. The pore space of volcanic reservoirs in Junggar Basin are divided into three types: primary pores, secondary pores and microfractures, and can be further subdivided into 16 subtypes. By lithologies, the volcanic reservoirs with the best physical properties are welded (vesicle) basalt, amygdaloidal (vesicle) andesite, volcanic breccia, welded (vesicle) tuff, rhyolitic dacite, amygdaloidal basaltic andesite and vesicle basaltic andesite.

(2) Comprehensively considering the three elements of source rocks, reservoir types and trap types, volcanic reservoirs in Junggar Basin are divided into two categories: self-generating & self-storing pattern and young-generating & old-storing pattern, and further divided into 10 types. In western Junggar, hydrocarbons mainly accumulated along fault zones; in eastern Junggar, hydrocarbons mainly accumulated along inherited uplift zones. Different tectonic patterns determine that there are four hydrocarbon accumulation patterns of the Carboniferous volcanic reservoirs in Junggar Basin: self-generating & self-storing in paleo-uplift and vertical migration, self-generating & self-storing in paleo-uplift and lateral migration, young-generating & old-storing in fault zone and vertical migration, and young-generating & old-storing in paleo-uplift and lateral migration. Hydrocarbon accumulation is mainly controlled by oil/gas-source fault+lithology (lithofacies)+unconformity in the tectonic setting.

(3) Future exploration of the Carboniferous volcanic rocks in Junggar Basin will focus on the effective source rocks development and hydrocarbon supply zones and the self-generating & self-storing and young-generating & old-storing patterns. The exploration prospects are determined to be the Ludong-Wucaiwan-Baijiahai slope belt and the southern slope belt of the Shaqi uplift (self-generating & self-storing pattern) in eastern Junggar, and the fault and nasal arch zone at the northwestern margin and the nasal arch zone (deep and large structure, such as Mahu anticline and Mosuowan anticline) in the Luxi area (young-generating & old-storing pattern) in western Junggar.

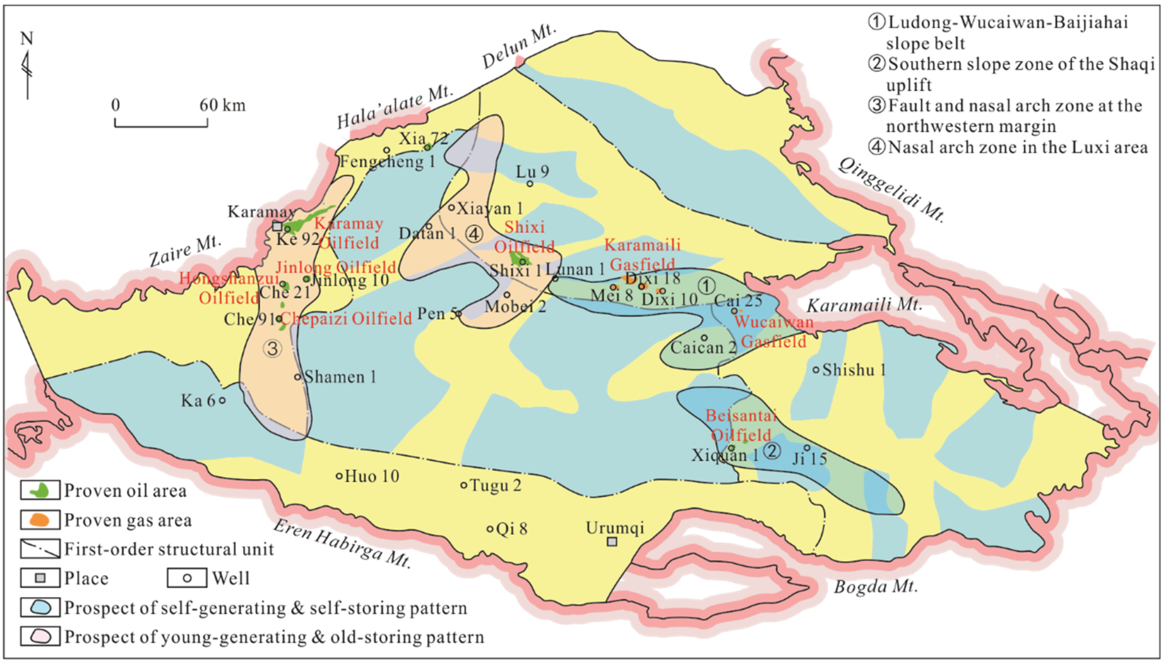

Figure 8. Distribution of exploration prospects in the Carboniferous volcanic rocks in Junggar Basin (the base map is modified after the internal data of Xinjiang Oilfield).

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