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# Review of volcanic reservoir geology in China

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A B S T R A C T

Volcanic reservoirs are widely distributed in more than 40 basins in 13 countries and have become an important target for oil and gas exploration. The study of volcanic reservoirs is becoming a hot research topic. After decades of research in China, especially within the last 20 years, numerous achievements have been attained including the study of void space, petrophysical characteristics, distribution pattern and reservoir origin. The research shows that the volcanic void space can be divided into 11 types and 27 subtypes. Volcanic rocks can be rich in primary vesicles, shrinkage fractures and explosive fractures, which are only found in volcanic rocks. Generally, the porosity and permeability values of volcanic rocks in basins are low, and pore throat values are small. Sometimes, sweet spots occur. Volcanic reservoir formation correlates with burial depth. In China basins, the porosity and permeability values of pyroclastic rock and tuffite buried above a depth of 3 km are higher than those of lava and welded pyroclastic rocks, while these values are reversed below a depth of 3 km. In general, all kinds of lithologies can bear hydrocarbons in basins, but only certain lithologies can bear oil and/or gas in specific blocks. The distribution model of the reservoir correlates the volcanic stratigraphic units; for example, it identifies the "good upper flow crust and poor lower flow crust" pattern formed by the lava flow and lava dome and finds the porosity and permeability values in the lava flow to be higher than those in the lava dome. The porosity and permeability values of the crater and near crater belt of the volcanic edifices are better than those of the proximal belt and the distal belt. Most favorable reservoirs are located within 200 m below the eruptive interval unconformity boundary or tectonic unconformity boundary. Release of volatiles, cooling and quenching, pre-burial weathering and devitrification are the important processes of volcanic reservoir formation. The deformation of lava during compaction processes is small, while that of pyroclastic rock is significant. The high content of unstable components in acidic fluid can provide the material for alteration and/or dissolution. A volcanic reservoir in a basin is the result of the above types of diagenesis and forms from a complicated origin process. The reservoir evolution process becomes more complicated when volcanic strata have undergone uplift and re-burial. With an increase in burial depth, the lava can preserve its original shape, which is beneficial to the preservation of vesicle, mold and sieve porosities. When the burial depth of pyroclastic rock increases, due to the increase in stress, displacement or crushing may occur between particles as they try to achieve a new support balance. Additionally, the diameter of intergranular pores probably decreases significantly, while the number pores may increase slightly. The primary porosity and secondary porosity that are generated during the eruptive, weathering and shallow burial stages can be damaged during the adjustment of particle support. At this moment, research on the characteristics and distribution patterns of volcanic reservoirs is at a quantitative level, while research on reservoir origin is at a qualitative level. The next stage of reservoir research should focus on the enhancement of the reservoir model based on volcanostratigraphic units and quantitative research on reservoir diagenesis.

## 1. Introduction

Gas and oil pools and oil in igneous intervals have been discovered with oil and gas occurring in more than 300 basins or blocks in more than 50 countries around the world (Dun, 1995; Shu et al., 1997; Schutter, 2003; Xu et al., 2006; Liu et al., 2010a, 2010b; Rabbel et al., 2021). Among them, 40 basins in 13 countries have developed oil and gas wells and large-scale reserves. In recent years, prolific oil and gas

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reservoirs have been found in the volcanic rocks of many basins in China (Feng, 2008; Zou et al., 2008; Feng et al., 2014; Chang et al., 2019; Wen et al., 2019; He et al., 2020; Zhu et al., 2020a; Mao et al., 2021; Jia et al., 2021), which confirms the good hydrocarbon holding capacity of volcanic reservoirs. Volcanic reservoirs have become an important focus of global oil and gas exploration and development (Polyansky et al., 2003; Shi et al., 2019; Stagpoole and Funnell, 2001; Feng, 2006; Lu et al., 2010). In terms of distribution range, the proportion of volcanic reservoirs in the circum-Pacific tectonic region is relatively high (Fig. 1). In terms of age, the global volcanic reservoirs are mostly concentrated in Meso-Cenozoic rocks (about 70%), followed by Paleozoic (Lv et al., 2003; Yang et al., 2006; Jin et al., 2007a, 2007b; Filhoa et al., 2008; Xing et al., 2021).

By 2019, the proven reserves in China volcanic reservoirs were 600 million cubic meters of oil and 580 billion cubic meters of gas from volcanic rocks (Xie et al., 2021). A series of theories and techniques exist for exploration and development of volcanic reservoirs (Meng et al., 2002; Xie and Zhou, 2008; Zhao et al., 2009a, 2009b; Zhang et al., 2010), especially since 2007 when a rapid development period was initiated. Overall, the exploration process of volcanic reservoirs in a block can be divided into four stages. For example, in the Songliao Basin, the four stages are: (1) exploration stage of secondary targets (before 1985); (2) targeted exploration stage (1985–2000); (3) exploration breakthrough stage (2000–2004); and (4) exploration development stage (2004–present) (Zhao et al., 2008), after which stable productivity was obtained. Volcanic rock exploration in other blocks has been similar, but with different time nodes (He et al., 1999).

The key issues of geological research of volcanic reservoir include reservoir characteristics, spatial distribution, origin and controlling factors (Uliana et al., 1989; Luo et al., 2003; Niu et al., 2003; Wang and Feng, 2008; Antonio et al., 2012; Chen et al., 2012). Volcanic reservoirs have distinctive characteristics, such as the development of vesicles and primary fractures, a high content of compositions soluble in acidic conditions, which is conducive to the formation of secondary pores, and weathering and leaching processes prior to burial. Even the existence of volcanic materials in sedimentary rocks is beneficial in preventing siliceous filling of intergranular pores and promoting the preservation of pores (Berger et al., 2009; Gao et al., 2018). To systematically analyze the particularity and research progress on volcanic reservoirs in China, the authors summarize and discuss the geological research results of volcanic rock reservoirs (mainly pertaining to reservoir space types, petrophysical characteristics, spatial distribution and origin), and analyze the degree of research conducted on volcanic reservoirs. It is hoped that this paper can arouse the attention to scholars on the geological theory of volcanic reservoirs.

## 2. Reservoir space

### 2.1. Types

According to the formation process and geometric characteristics, the reservoir space can be divided into primary and secondary pores and fractures (Ren and Jin, 1999; Sruoga et al., 2004; Wang et al., 2013a, 2013b, 2015). Based on the genesis and distribution characteristics, the reservoir space can be divided into 11 types and 27 subtypes, including three types and five subtypes of primary pores, two types and nine subtypes of primary fractures, three types and seven subtypes of secondary pores and three types and six subtypes of secondary fractures. See Table 1 and Fig. 2 for details. The primary pores are mainly intergranular pores and vesicles (including amygdales), while the secondary pores are mainly moldic pores, sieve pores and sponge pores. The primary fractures can be divided into shrinkage fractures (including quench fractures, columnar joints, platy fractures, suture-like fractures, macro-tortoise shell joints and micro-tortoise shell joints) and explosive fractures (intraparticle explosive cracks, such as minerals and lithics), cryptoexplosive cracks (some of which may be formed in late magmatic activities), and secondary fractures include tectonic fractures, weathered fractures and dissolution fractures. The tectonic fractures are related to the stress properties, the reticular cracks can form in the tensile environment, and the high-angle conjugated joints can be produced in the compressive environment. In the weathering fractures, there are unloaded joints and spherical weathering fractures, and the dissolution joints can be generated from any crack. When primary pores are superimposed with secondary pores, the difficulty of pore type identification is increased; similarly, primary and secondary fractures can be superimposed with dissolution and filling, which makes the fracture morphology complicated.

Studies show that the primary pores of volcanic rocks are closely related to facies architecture (Gu et al., 2002; Chen et al., 2003; Wu et al., 2006; Jerram et al., 2009; Watton et al., 2014; Millett et al.,

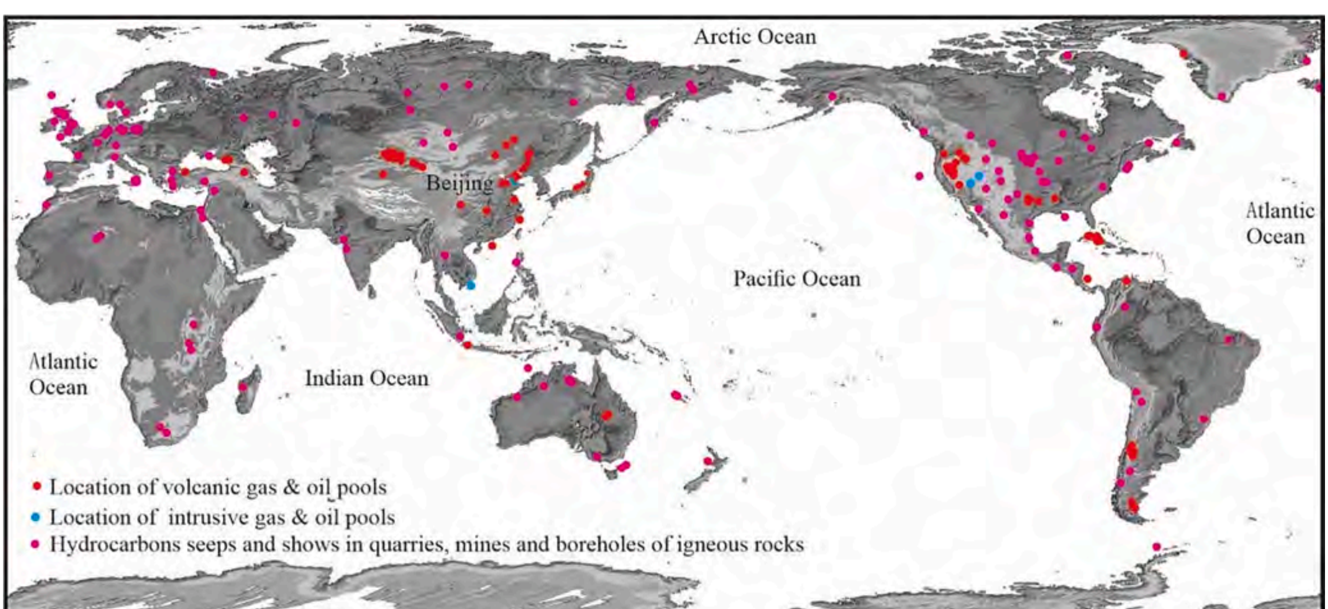


**Fig. 1.** The location of the oil and gas pool in the igneous rocks and the hydrocarbons associated with the igneous rocks (based on Schutter, 2003; Liu et al., 2010a, 2010b; Zou et al., 2008; Wen et al., 2019).

**Table 1**
Classification of void spaces in volcanic rocks.

| Formation stages | Geometry | Types/subtypes | | Origins | Characteristics | Spatial distribution |
|---|---|---|---|---|---|---|
| Primary | Pores | Vesicle phyla | Vesicle | The volatiles (water, carbon dioxide, fluorine, chlorine, and other components) in the lava degassed during decompression as the magma rose, producing bubbles, which were frozen in the rocks during the cooling process when the magma was ejected onto the surface. | The shapes are mainly spherical, ellipsoidal, or tubular. The diameter ranges from mm to cm, and the distribution is linear directional or discrete. The connectivity is positively correlated with the porosity of the pores and the fracture intensity. | Rhyolitic/andesitic/basaltic simple-braided lava flows are common at the top, and the porosity can decrease with increasing distance from the vent. |
| | | | Lithophysae | During the consolidation of a lava rich in volatile matter, the gas escapes and expands, creating cavities, the walls of which are composed of multilayer concentric radial fibers of potassium feldspar or felsic material. | The shape is spheroidal or ellipsoidal, and the diameter is several centimeters. The shrinkage fractures along the pore walls may have good connectivity. | Simple rhyolitic lava flows are common at the top. |
| | | | Amygdale | The vesicles in the lava are filled with minerals (e.g., calcite, quartz, and chalcedony), forming an almond like structure. | The intergranular micropores between the filling material and the residual pores in the unfilled part of the amygdale have an irregular shape. | Basaltic/andesitic simple-braided lava flows are common in the top part. |
| | | Intergranular pores | | A pore preserved via the support of pyroclastic particles (usually lithic and crystalline) forms a skeleton and is incompletely filled by matrix and cement materials. | Irregular shape, usually along the edge of particles, good connectivity | Pyroclastic flow, base surge, underwater pyroclastics, and reworked volcaniclastic deposits are common. |
| | | Melted pores | | When the magma from deep underground carries high-temperature quartz and sanidine to the shallow part or is ejected onto the surface, the phenocrysts are melted and pores are formed as the melting point of the minerals decreases with decreasing static pressure. | Bay-shaped, rounded, and sieve-shaped, poor connectivity | The phenocrysts in the porphyritic rocks and the crystal pyroclasts in tuffaceous lava |
| | | Shrinkage fractures | Quench fractures | When the lava erupts, it comes in contact with air, water, ice, or snow, and the lava is quenched and cools rapidly, forming fractures. | Radial and annular shapes, good connectivity | They are common in subaqueous lavas, such as pillow lava and vitric lava. |
| | | | Columnar joints | Due to the viscosity of the lava or the topography, the lava does not easily flow or is slow to cool without flowing. The lava is consolidated along the cooling center. Because the external part consolidates first, the internal lava undergoes nearly equal volume consolidation, resulting in fractures. | According to the geometry and cross-section of the cylinder, they can be divided into regular and irregular types. The cross-sectional polygons of cylinders are 3- to 8-sided, and the side length is several cm to dozens of cm. The columnar joints have excellent connectivity. | They can be seen in lava domes and in the middle and lower parts of simple lava flows. |
| | | | Platy fractures | During molten flow, due to the cooling effect, the flow velocity of the outer regions is lower than that of the internal region, resulting in shear stress, which forms fractures parallel to the flow direction. | Layered or flaky, good horizontal connectivity | Usually found in the lower part of a simple lava flow. |
| | | | Suture-like cooling fractures | During molten flow, the incompletely cooled shell has a rheological effect, which results in the formation of microcracks due to folding of the flow. | Tooth-shaped, poor continuity, poor connectivity | Rare, distributed at the base or top of lava flows |
| | | | Macro-tortoise shell joints | They are formed under conditions of approximately equal volume cooling and gravity traction during the flowing stage. The joint strike is perpendicular to the flowing direction. | The cross-section is an irregular polygon and a regular-irregular plane, and the connectivity is good. | In simple lava flows, they can penetrate the whole lava flow. |
| | | | Micro-tortoise shell joints (tiny normal joints) | They are formed under conditions of approximately equal volume cooling and moderate cooling rates during molten flow. | Irregular microfractures with medium connectivity and limited distribution | They can be seen in the several centimeters to tens of centimeter zones at the base or top parts of lava flows and lava domes. |
| | | Explosive fractures | Pressure loss cracks | During magma ascent, the pressure of the lava decreases. The magma volume expands, which causes the minerals to generate cracks. | The crystal surface is irregular or multiaxial. | Usually found in lava with phenocrysts or pyroclastic rocks with crystalline fragments |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Magma fragmentation fractures | If the force of the gas expansion due to the ΔP at the magma-atmosphere interface is greater than the tensile strength of the matrix skeleton, fragmentation occurs. Some cracks are preserved in particles or minerals. | Explosive cracks in pyroclastic rocks, good connectivity | In pyroclastic rocks |
| | | | Crypto-explosive fractures | In hypabyssal and ultrahypabyssal environments, fractures form due to the explosive activity when the pressure on the top part of the magma is greater than the tensile strength of the host rocks. | Branched and reticulate, often filled with ichor, and they have a high porosity and permeability when the degree of filling is low. | They are common in the vicinity of the volcanic conduits of intermediate-felsic edifices |
| Secondary | Pores | Dissolution/alteration pores | Moldic pores | Pores formed by the complete dissolution of minerals (pyroxene, hornblende, and feldspar) in rocks | The pore morphology is regular. The pseudomorph is retained. Good connectivity, strong dissolution intensity | They are common in rocks with primary fractures. |
| | | | Sieve pores | Pores formed by the dissolution or alteration of minerals (pyroxene, hornblende, and feldspar) in rocks in some areas | Small size, medium connectivity, medium dissolution intensity | They are common in lava with primary fractures and pyroclastic rocks with primary pores. |
| | | | Cavernous pores | Pores in a rock resulting from matrix dissolution | Large size, good connectivity, strong dissolution intensity | They are common in pyroclastic rocks rich in primary pores. |
| | | | Intragranular micropores | Micropores formed by partial dissolution of minerals (pyroxene, hornblende, and feldspar) in rocks | Small size, medium connectivity, weak dissolution intensity | They are common in lava with primary fractures and pyroclastic rocks with primary pores. |
| | | | Spongy pores in matrix (lacy) | Pores in the matrix resulting from partial dissolution or alteration | Small size, bad connectivity, weak dissolution intensity | They are common in pyroclastic rocks rich in primary pores. |
| | | Recrystallization micropores | Devitrified micropores | Vitrification of vitric matter in rocks | Small to large size, good to medium connectivity, representing increases in temperature and pressure | They are common in obsidian, rhyolite, and basalt. |
| | | Intergranular pores in fault breccia | | Pores between fault breccia filled by structural fractures | Irregular fault breccia shape, mainly intergranular pores, good connectivity | They are common in fault zones. |
| | Fractures | Weathering fractures | platy weathering fractures | When deeply buried dense massive volcanic rocks are uplifted and exposed at the surface, layered cracks are formed by the expansion of the surface rock due to the unloading of the loading force. | They extend along the topography, and the intervals between the fractures increase with depth. | Top part of weathering crust |
| | | | Stress relief micro-fractures | When deeply buried pyroclastic rocks with a poor degree of cementation are uplifted and exposed at the surface, microcracks are produced in the grains and at the grain edges due to the unloading of the loading force. | The direction is uncertain, and the shape is diverse. | Top part of weathering crust |
| | | | Spherical weathering fractures | Generally, the rock is cut into small polyhedral pieces by joints with no less than three groups of directions. The edges and corners of small rocks are destroyed first by weathering (temperature, water solutions, and other factors) from multiple directions, and then, the rock is weakened toward the interior. Due to the difference in weathering strength, a circular layer is formed, leading to the formation of fractures. | Concentric circles, ellipse | Top part of weathering crust, massive lava undergoing structural transformation A lava with columnar joints is easier to produce. |
| | | Tectonic fractures | Shear tectonic fractures | They are caused by shear stress after consolidation. | Fractures with high angles and straight planes | They can be developed in dense lava and pyroclastic rocks |
| | | | Tensile tectonic fractures | They are caused by tensile tectonic stress after consolidation. | Reticular, irregular, good connectivity | They can be developed in dense lava, clastic lava, and pyroclastic rocks. |
| | | Dissolution fractures | | The above-mentioned fractures are dissolved by meteoric water and the formation fluid. | Based on the existing morphology, they can be transformed into various geometries. | They are common in areas that are rich in primary fractures and tectonic fractures and are in contact with fluids. |

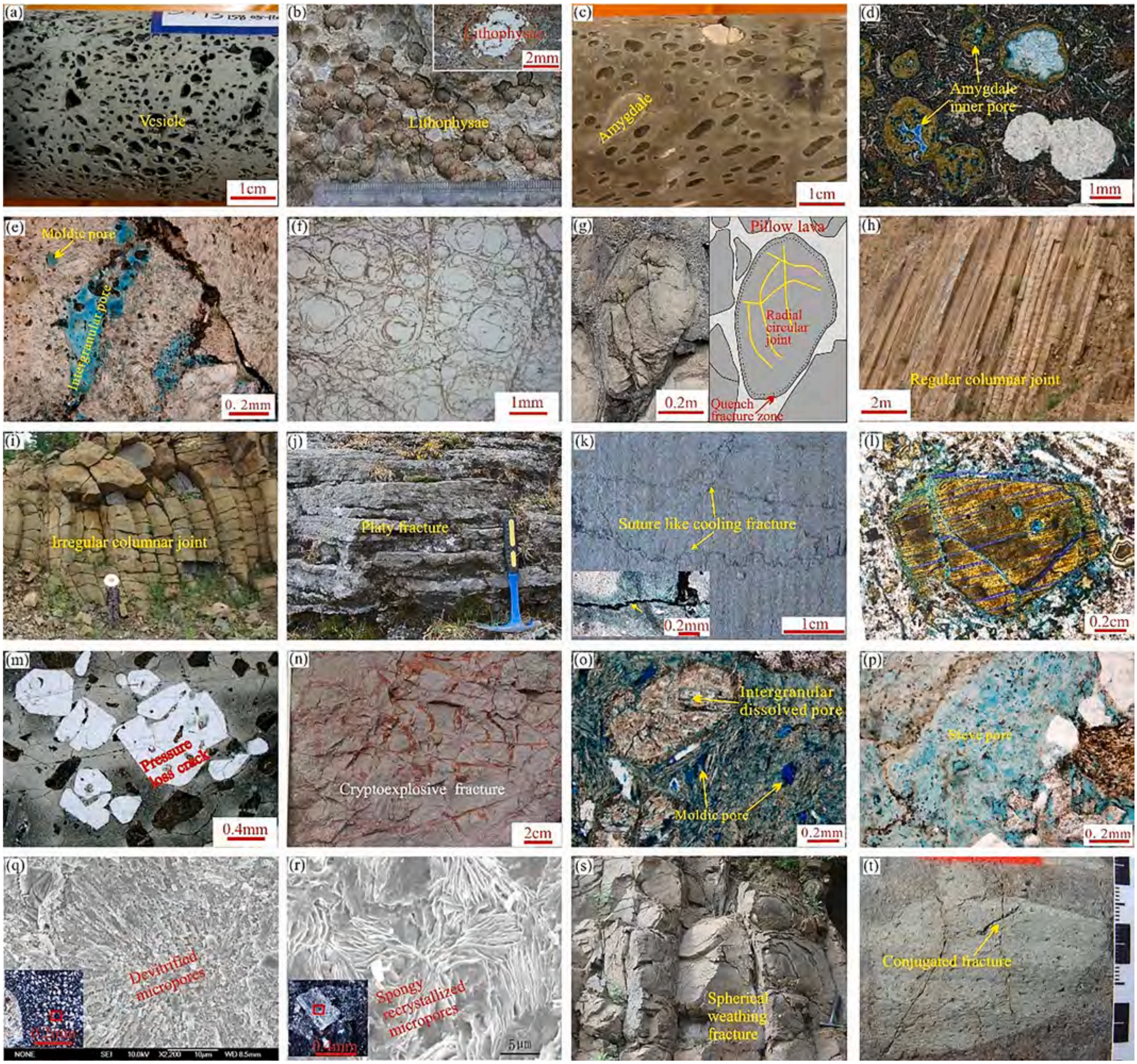


**Fig. 2.** The characteristics of the void spaces in the volcanic rocks.
(a) Well D1 (161.05 m) in Jiutaiying 3, Jilin Province, Early Cretaceous Yingcheng Formation, basalt and pore structure; (b) Early Cretaceous Yingcheng Formation, quarry, Shichang Village, Liutai Township, Jilin Province, rhyolite, amygdale; (c) Well D1 (113.85 m) in Jiutaiying 3, Jilin Province, Early Cretaceous Yingcheng Formation, basalt and residual amygdale pores; (d) Well Jia31 (3731.34 m) in Oligocene Shahejie Formation, Liaohe depression, Liaohe Basin, basalt, amygdale inner pore; (e) Well CS6 (2533.85 m) in Shahezi Formation, Wangfu sag, Songliao Basin, sed-volcanic agglomerate, intergranular pore and moldic pore; (f) Early Cretaceous Yingcheng Formation in Santai County, Jiutai City, Jilin Province, perlite, shrinkage fracture; (g) Permian Qiaoqi profile in Sichuan province, pillow-like basalt, quench fracture developed at the edge of the pillow lobe, radial circular joints developed in the middle; (h) Early Cretaceous Yingcheng Formation in Shanmen Town, Siping County, Jilin Province, rhyolite, regular columnar joints; (i) Pleistocene bimodal basalts from ManJiang town quarry, Jilin Province, deformed columnar joints; (j) On the northern slope of Tianchi in Changbai Mountain, pantellerite, stratified condensation-shear fracture; (k) Early Cretaceous Yingcheng Formation in well DS17 (2234.54 m) in the Dehui fault depression, dacite, suture-like line shrinkage fractures; (l) Well Xiao10 (1998.3 m) in Liaohe eastern depression, Liaohe Basin, hornblende pressure loss cracks; (m) Early Cretaceous Yingcheng Formation in well Xushen 1 (3528 m) in the Xujiaweizi fault depression, ignimbrite, explosion cracks in quartz; (n) Early Cretaceous Yingcheng Formation in Jiutai, Jilin Province, crypto-explosive crack; (o) Well Hong38 (4411.79 m) in Oligocene Shahejie Formation, Liaohe depression, Liaohe Basin, trachyte, intergranular dissolved pore and moldic pore; (p) Early Cretaceous Shahezi Formation in well CS6 (2526.75 m) in Wangfu sag, Songliao Basin, sed-volcanic breccia, sieve pore; (q) Early Cretaceous Yingcheng Formation in well Longshen 201 (3603 m) in the Yingtai fault depression, the rhyolite and matrix have been devitrified to form spherulites and intergranular micropores; (r) Early Cretaceous Yingcheng Formation in well Longshen 301 (3046 m) in the Yingtai fault depression, rhyolite, alkaline feldspar phenocrysts have been dissolved to form lamellar illite intercrystalline micropores; (s) Oligocene Dagushan Formation in Siping toll station, columnar jointed basalt with spherical weathering fractures; (t) Well CS6 (2528.3 m) in Shahezi Formation, Wangfu sag, Songliao Basin, sed-volcanic agglomerate, conjugated fracture.

2021b). Based on the study of volcanic profiles in Songliao Basin and its surrounding areas, the upper flow crust of the lava flow is mainly composed of primary pores such as vesicles and amygdales, while the lower flow crust of the lava flow is dominated by shrinkage fractures, and the subaqueous lava develops abundant quench fractures (Single and Jerram, 2004; Bear and Cas, 2007; Tang et al., 2013; Tang et al., 2017a, 2017b). The pyroclastic flows develop abundant intergranular pores, intragranular vesicle and tensile fracture (Liu et al., 2003; Branney et al., 2004; Sruoga et al., 2004; Andrews and Branney, 2011; Wu et al., 2011; Sumner and Branney, 2002). The lava domes develop abundant shrinkage fractures and vesicles (Mueller et al., 2005; Farquharson et al., 2016; Tang et al., 2020a). Secondary pores are generated by weathering, burial dissolution or alteration, tectonism and devitrification (Luo et al., 1999; Kawamoto, 2001; Othman and Ward, 2002; Volk et al., 2002; Sruoga and Rubinstein, 2007); the weathering, burial dissolution or alteration processes are related to the connected primary pores and fractures.

### 2.2. Characteristics of void space assemblage

As evidenced from volcanic reservoirs that have been discovered, the reservoir space is typically a combination of primary pore and secondary pore types. Due to the diversity of pores and fractures, the combined types of reservoir space that have formed are very complex, and vary between different basins/blocks. For example, combinations formed in the Cretaceous Yingcheng formation in the Songliao Basin include vesicle-dissolution pore-fracture, vesicle-fracture, intergranular pore-dissolution pore-fracture and intergranular pore-dissolution pore-fracture (Liu et al., 2003; Shi et al., 2011; Zhang, 2013). Among these, the porosity and permeability values of the vesicle-dissolution pore-tectonic fracture combination are higher than those of other assemblages (Wu et al., 2005). The volcanic rocks in the Junggar Basin are composed of four pore type combinations, tectonic fracture-dissolution fracture-dissolution pore, primary vesicle-tectonic fracture-dissolution pore, intercrystalline pore-dissolution pore and fracture type (Lin et al., 2011; Zhao and Shi, 2012; Fan et al., 2014, 2020; Wang et al., 2014; Zhang et al., 2014). There are two pore type combinations in the volcanic rocks of the Santanghu Basin, the primary vesicle-dissolution pore combination and the tectonic fracture-dissolution pore-intergranular pore combination (Liu et al., 2009; Li et al., 2014a, 2014b; Chen et al., 2021). The Cenozoic volcanic reservoir in the eastern sag of the Liaohe Basin reservoir includes fracture type, fracture-pore, weathering and leaching fracture-pore (Qiu et al., 2000). Two types (pore-vesicle type and fracture type) have developed in the Bohai Bay Basin (Jiang et al., 2012; Wang et al., 2021a). Fractures in some intervals contribute up to 90% to the reservoir space (Cao et al., 1999).

Different combinations of reservoir space types have a significant impact on the physical characteristics of the reservoir. For example, Wells Y1D1 and Y3D1 in the southeastern margin of Songliao Basin reveal that the permeability of fractured reservoirs increases rapidly with an increase in porosity. The permeability of the pore-fracture reservoir increases with porosity over a gentle slope while the permeability of the intergranular pore-fracture type reservoir increases with porosity over a moderate slope (Xiu et al., 2016) (Fig. 3). In comparing the volcanic reservoir spaces in China, the eastern basins mainly contain the primary type, while the western basins mainly contain the secondary type (Zhu et al., 2010).

## 3. Petrophysical characteristics

The physical properties of reservoirs contained within each basin or block vary greatly, as well as between basins or blocks (Fig. 4). Volcanic rock generally contains medium and low porosity, medium and low permeability and small pore throat reservoirs, which are also known as tight reservoirs in some basins (Wang et al., 2008; Wang et al., 2011a, 2011b; Zou et al., 2013; Meng et al., 2014; Bai et al., 2021); however, high porosity and medium and high permeability reservoirs can develop locally. Volcanic rocks exhibit strong reservoir heterogeneity, which is closely related to the rock fabric, mineral composition and pore structure (Liu et al., 1999; Chen, 2012; Gan et al., 2013). There is a good correlation between the average throat radius and permeability. The pore-throat ratio of volcanic rock is very large, the irreducible water saturation is high, and there is a threshold pressure gradient (Pang et al., 2007; Farquharson et al., 2015). The porosity cutoff of oil storage in volcanic rock reservoirs is low, such as 5.0% tuff and 4.5% lava in District No. 9 of the Karamay oilfield, where both tuff and lava occur below sedimentary rocks at the same burial depth (Tang, 2011), indicating that volcanic rocks have good potential as effective reservoirs.

The porosity, permeability and pore throat values of volcaniclastic rocks decrease when the confining pressure increases (Peng et al., 2004; Heap et al., 2018), and the permeability value cannot be reset to the initial value when the confining pressure is unloaded (Fan et al., 2018). With an increase in confining pressure, the pore permeability decreases for samples with a large initial porosity (Entwisle et al., 2005). When the porosity is less than 20%, the threshold pressure is reduced rapidly with increasing porosity. The threshold pressure of the fracture does not decrease significantly when the porosity is larger than 20% (Spieler et al., 2004). For porous samples, the permeability reduction rate is

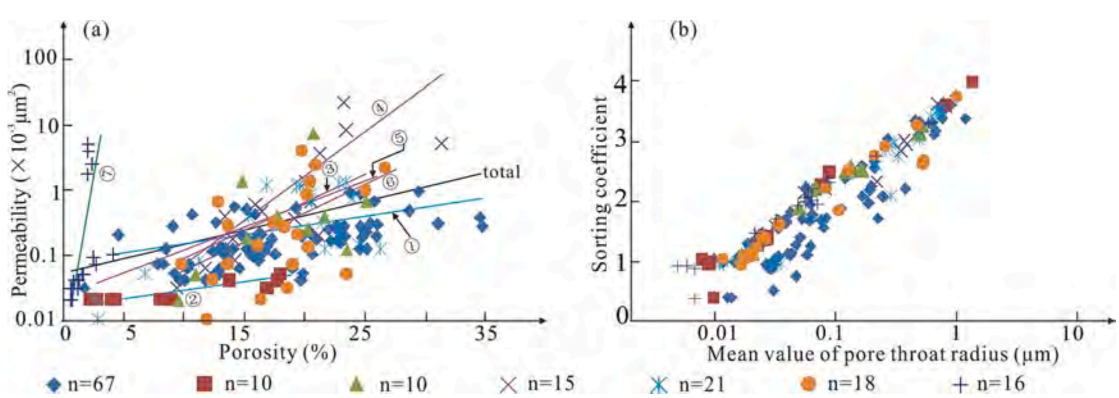


**Fig. 3.** Reservoir characteristics of the pore-fracture units of the volcanic rocks of the Yingcheng Formation in wells Y1D1 and Y3D1 in the uplift area in the SE Songliao Basin, China.

Notes: type ①: scatter vesicles + secondary fractures; type ②: orientation vesicles + devitrification pores; type ③: scatter intergranular pores + dissolution/alteration pores; type ④: scatter intergranular pores + dissolution/alteration pores + primary fractures; type ⑤: scatter intergranular pores + dissolution/alteration pores + secondary fractures; type ⑥: orientation intergranular pores + alteration pores + secondary fractures; type ⑦: fractures; and n is the sample number. Relationship between porosity and permeability: type ①, $K = 0.0615e^{0.0559\varphi}$; type ②, $K = 0.0159e^{0.0514\varphi}$; type ③, $K = 0.0135e^{0.1713\varphi}$; type ④, $K = 0.0037e^{0.276\varphi}$; type ⑤, $K = 0.0208e^{0.1422\varphi}$; type ⑥ $K = 0.0081e^{0.1796\varphi}$; and type ⑦, $K = 0.0071e^{1.8296\varphi}$.

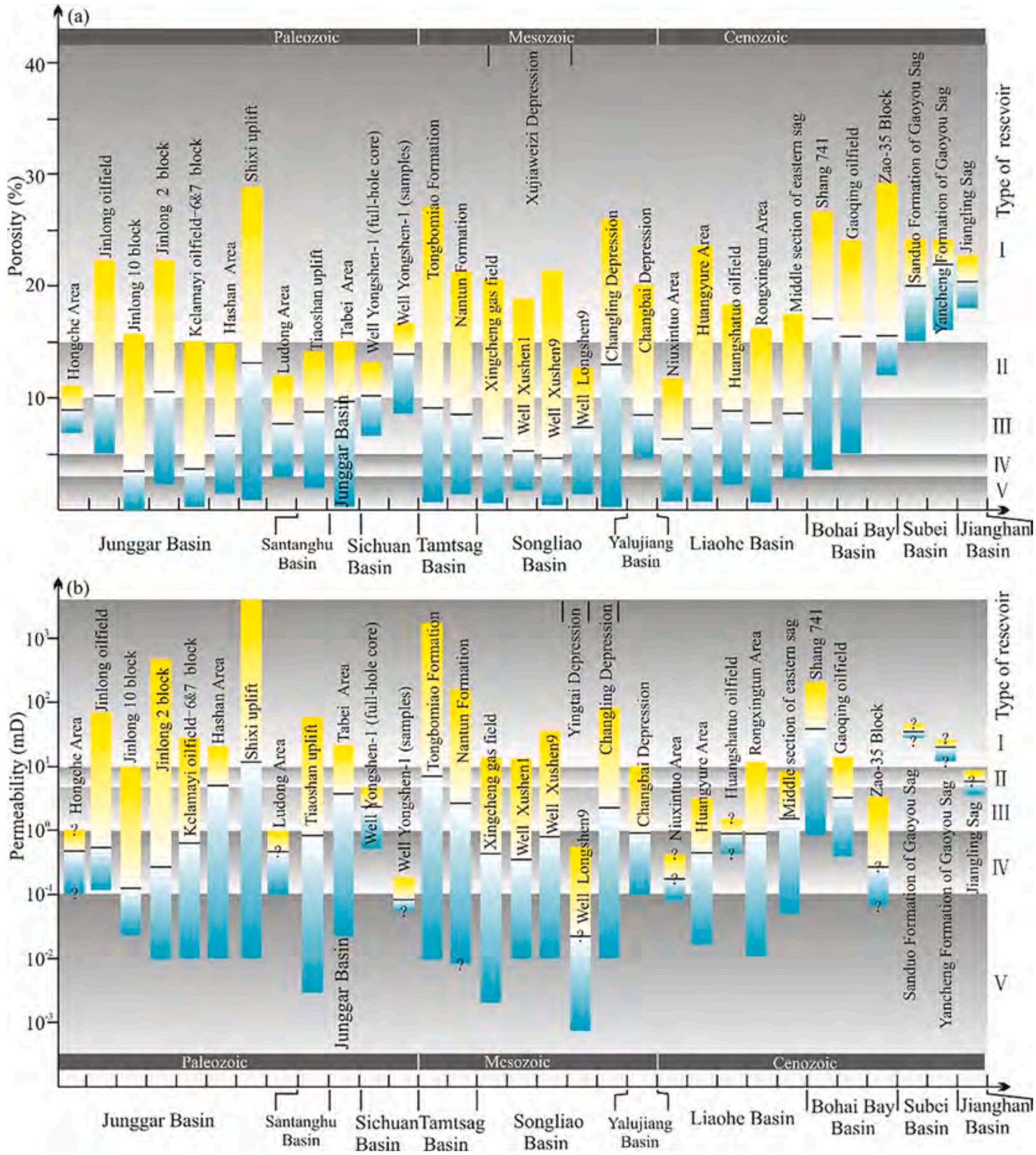


**Fig. 4.** The porosity and permeability characteristics of volcanic rocks. (a) Characteristic of porosity in different basin/block; (b) Characteristic of permeability in different basin/block.

Note: the top and bottom (yellow and light blue) of the rectangle in the figure represent the maximum values of the porosity and permeability, respectively. The black lines represent the average values of the porosity and permeability. In addition to the data from the Taranaki Basin, the other sources are from the document (a, b from Tang et al. (2020c)). The permeability is a geometric average. The classification standard of the porosity and permeability is in accordance with the petroleum industry standard of the People's Republic of China (SY/T 6285–2011 oil and gas reservoir evaluation method).? denotes no data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

small when the confining pressure increases (Cant et al., 2018). For fractured reservoirs, such as rhyolite and tuff in Daqing volcanic reservoir, the more developed the fractures are, the stronger the stress sensitivity is (Hu et al., 2006), and, meantime, the more the permeability of water-bearing rock samples decreases with increasing effective pressure compared to dry rock samples. Once the low-pressure section is compressed, the fracture will close and the permeability will decrease faster, while the rate of decrease in the high pressure section will slow down (Zhu et al., 2007) (Fig. 5).

For reservoir evaluation, it is necessary to integrate information from all parameters such as reservoir space type and combinations, petrophysical properties and microscopic pore structure characteristics in order to establish a reasonable relationship with productivity (Jin et al., 2007a, 2007b; Yan et al., 2011; Chen et al., 2016a, 2016b; Ma et al., 2017; Huang et al., 2019). Reservoir correlation should be studied under the constraint of a high-resolution stratigraphic framework (Tang et al., 2010; Chen, 2012). Rock wettability is controlled by the acidity of the crude oil, and the Amott water index decreases exponentially with increasing acidity, which affects oil liquidity and the oil recovery ratio (Xie et al., 2010).

## 4. Spatial distribution of volcanic reservoirs

The study of volcanic reservoirs is generally divided into two stages. Stage I: Establishing the relationships of reservoir vs. lithology, reservoir vs. facies architecture and reservoir vs. burial depth. Stage II: The relationships of reservoir vs. stratigraphic unit and reservoir vs. boundary are established based on the spatio-temporal attributes of

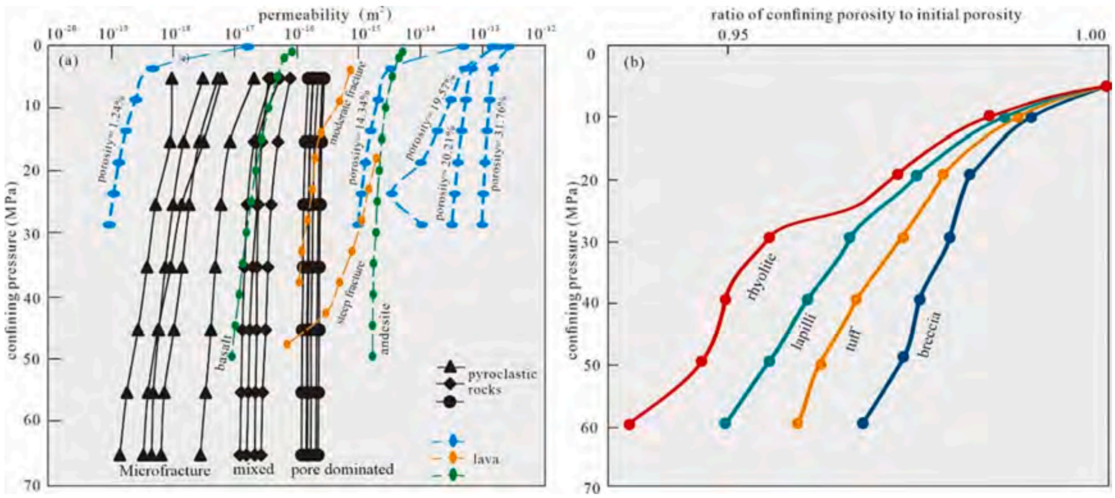


**Fig. 5.** Variations in the permeability and porosity of the volcanic rock reservoirs with confining pressure. (a) Permeability vs. confining pressure; (b) Ratio of confining porosity to initial porosity vs. confining pressure.
Note: (a) the black lines are from Cant et al. (2018). The blue lines are from Lamur et al. (2017). The orange lines are from Fan et al. (2018). The green lines are from Heap et al. (2018). (b) The data are from Zhu et al. (2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

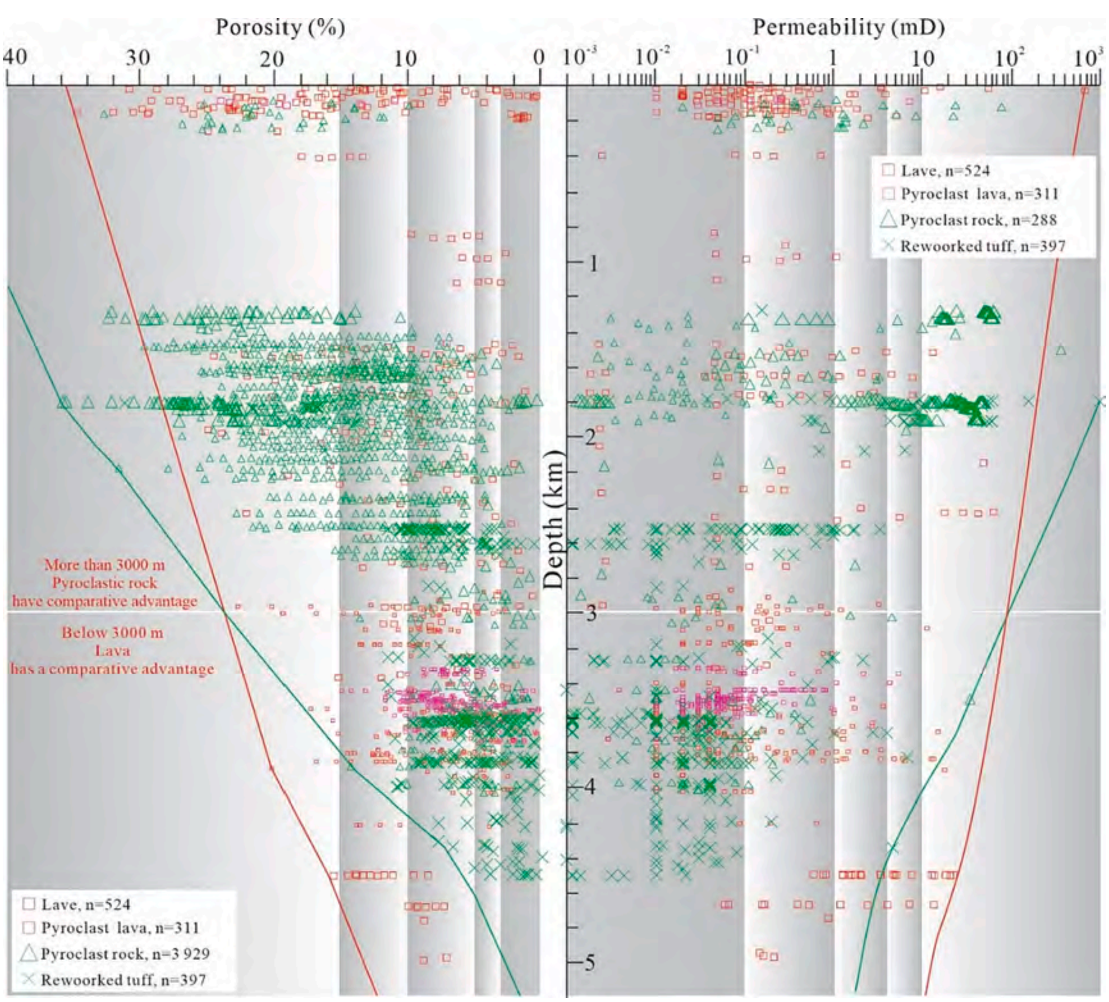


**Fig. 6.** Relationships between porosity and depth and between permeability and depth in China.
Notes: Data sources, including for the Songliao Basin (Wang and Chen, 2015; Tang et al., 2016a), Tamtsag Basin (Zhang et al., 2012), Hailar Basin (Xiao et al., 2011), Santanghu Basin (Li et al., 2014a, 2014b), Tarim Basin (Sang et al., 2012), and other data are from this paper. The lavas are from the Songliao Basin (349), the Santanghu Basin (155), and the Tarim Basin (20). The welded pyroclastic rocks are from the Songliao Basin (311). The pyroclastic rocks are from the Songliao Basin (94), the Hailar Basin (3641), the Santanghu Basin (53). The tuffites are from the Songliao Basin (357).

volcanostratigraphy. The two research stages are described in detail below.

### 4.1. Stage I of research

#### 4.1.1. Relationship between burial depth and porosity–permeability

The porosity and permeability values of the core tend to decrease with an increase in burial depth (Fig. 6), but more primary pores can be preserved in the deep layer, which may have a superior petrophysical property effect. The decrease in the porosity and permeability of lava with increasing burial depth is smaller than that of pyroclastic rocks and tuffite; the maximum porosity and permeability of lava at depth is greater than that of pyroclastic rocks and sed-volcanic pyroclastic rocks. Generally, pyroclastic rocks and tuffite can have high porosity and permeability values when buried depth above 3000 m, and lava can still have high porosity values when buried deep below 3000 m (Wang and Chen, 2015). Pyroclastic rocks in the Tamtsag Basin and Hai Laer Basin became favorable reservoirs within the burial depth range of 1400–2800 m (Zhang et al., 2012). Variations exhibited by pyroclastic rocks and tuffite may also be related to the diameter of particles. With respect to tuffite, the range in variation of tuffaceous conglomerate/breccias is greater than that of sedimentary tuff; therefore, the tuffaceous conglomerate/breccias have more advantages in the deep layer (Tang et al., 2016a).

#### 4.1.2. Relationship between lithology and favorable reservoir

Based on texture and genesis, volcanic rocks can be divided into lava and pyroclastic rock. According to $SiO_2$ content, the lava can be divided into picrite, basalt, andesite, trachyte and rhyolite, among others (Le Maitre et al., 1989). Based on grain size, pyroclastic rocks can be divided into agglomerates, volcanic breccia and tuff (McPhie et al., 1993). Based on the composition and fabric characteristics, all kinds of volcanic rocks can be further divided (Sigurdsson, 1999; Wang et al., 2003a, 2003b; Wang et al., 2006). To date, an abundant number of volcanic rocks have been revealed by drilling in the China basins. As indicated by the conditions revealed in well blocks, lava reservoirs are the most common, accounting for 54%, followed by pyroclastic rocks that account for 38%, while ignimbrite reservoirs are the least common, accounting for only 8% (Fig. 7). All kinds of volcanic rocks of different compositions and diagenesis can develop reservoirs, but only certain lithologies in specific blocks can become favorable reservoir rocks as demonstrated by the following examples. Rhyolites have become favorable lithologic zones in the Xujiaweizi fault depression of Songliao Basin (Zhao et al., 2009a, 2009b; Wang, 2018), Changling fault depression (Cang et al., 2021), Nanbao Sag of Bohai Bay Basin (Xia et al., 2017), Ludong-Wucaiwan area of Junggar Basin (Fan et al., 2014; Yang et al., 2021). Trachytes have become favorable lithologic zones for reservoirs in the Xujiaweizi fault depression of Songliao Basin (Huang et al., 2017), and the Wangfu fault depression and Oubei-Dawan area of Liaohe Basin (Zhang et al., 2002; Tang et al., 2020c). Basalts have become favorable lithologic zones in the Xujiaweizi fault depression (Huang et al., 2010), Dehui fault depression (Du et al., 2012), Liaohe Basin (Shi and Hou, 2005), Beisantai area of Junggar Basin, and Niudong area of Santanghu Basin (Wang et al., 2010a, 2010b; Li et al., 2014a, 2014b; Yang et al., 2020). Ignimbrite rocks has become a favorable lithologic zone in the Sichuan Basin (Wen et al., 2019; Wang et al., 2021b; Xie et al., 2021), where the petro-physical property is inversely proportional to the welded intensity. Breccias have become favorable lithologic zones in the Linshang area/Nanbao Depression in the No. 5 tectonic belt (Wang et al., 2003a, 2003b; Xia et al., 2017), Kebai region of Junggar Basin/Hashan region/Jinlong Oilfield/Kelameili Gasfield (Lin et al., 2011; Zhang et al., 2013a, 2013b, 2013c; Yuan et al., 2015; Wang et al., 2017). Tuffs have become favorable lithologic zones in the northern Santai area of the Junggar Basin and Kebai area (Wang et al., 2010a, 2010b; Yuan et al., 2015). Sedimentary pyroclastic rocks have become favorable lithologic zones in the Luxi area of Junggar Basin (Ma et al., 2012; Xian et al., 2013), Sudeert structural belt in the Beier Sag of Hailaer Basin and Yingtai/Wangfu fault depression in Songliao Basin (Xiao et al., 2011; Tang et al., 2016a; Miao et al., 2020). Drilling has revealed that tuff is the most common reservoir rock, followed by basalt. The breccia lava reservoir is the least common (Fig. 7).

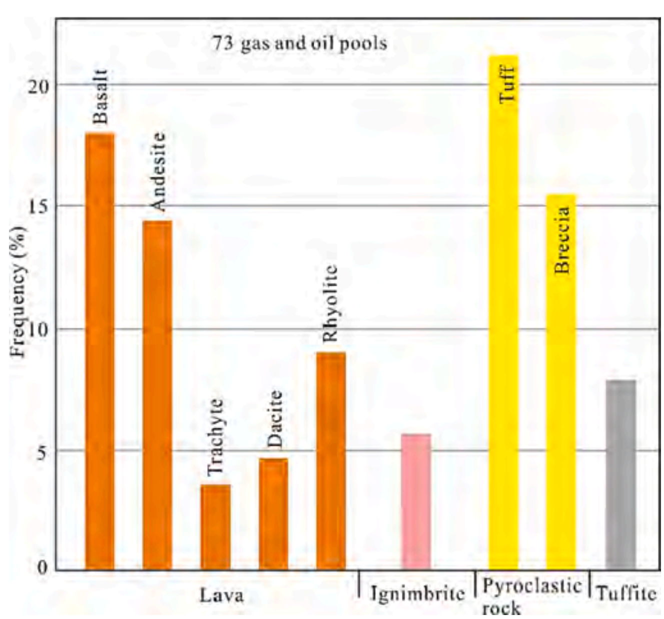


**Fig. 7.** Frequencies of occurrence of different lithologies in volcanic oil and gas pools in China.

### 4.2. Stage II of research

In order to further clarify the spatial distribution of volcanic reservoirs and extend the relationship between lithologic facies and reservoir to the three-dimensional stratigraphic range, it is necessary to analyze the spatial distribution of reservoirs under the constraint of volcanic stratigraphic units. The basic stratigraphic units include lava flow, lava dome, pyroclastic flow, base surge and lahar (Fisher and Schmincke, 1984; Cas and Wright, 1987; Xie, 1994; Batiza and White, 2000; Planke et al., 2000; Lockwood and Hazlett, 2010). The volcanic edifice is formed by the overlap of deposit units, and the volcanostratigraphy is formed by the overlap of volcanic edifices. There is an abundance of research that has been conducted on deposit units (mainly lava flows/lava domes), volcanic edifices and volcanostratigraphic boundaries (Annen et al., 2001; Hurwitz et al., 2003; Wang et al., 2010a, 2010b; Wang et al., 2011a, 2011b; Yi et al., 2015; Tang et al., 2017a, 2017b).

#### 4.2.1. Relationship between lava flow/lava dome and reservoir

(1) **Lava flow** A lateral, surficial outpouring of molten lava from a vent or a fissure; also, the solidified body of rock that is so formed (Fink, 1990; Sigurdsson, 1999; Neuendorf et al., 2011). It is usually cooled and consolidated into rock, and the rock texture and dip angle change continuously. The confinement boundary is mainly an eruption unconformity or eruption conformity (Smith, 2002; Tang et al., 2017b). Lava flows can also be divided into basalt, andesite, trachyte and rhyolite lava flows according to rock composition. According to their outer morphology, lava flows can also be divided into sheet-, plate-, shield- and mound-like flows (Sigurdsson, 1999; Jerram, 2002). Based on the eruptive environment, they can also be divided into subaqueous and subaerial eruptions (Piccoli, 1966; Carey and Sigurdsson, 1984; Batiza and White, 2000). Based on the overlapping relation, they can be divided into simple lava and braided lava flows (Single

and Jerram, 2004; Passey and Bell, 2007). A simple lava flow can be divided into flow interior, upper flow crust, lower flow crust, and brecciated flow margin intra-facies zones (Rowland and Walker, 1988; Millett et al., 2021a). The core and logging data reveal that lava flows in China basins are mainly the subaerial type. There are some examples of simple and braided lava flows in China basins. The simple lava flow when the orderly stack of platy lava is dominant, and braided lava flow when the staggered and disorderly overlapping of lava lobe is dominant (Fig. 8a–d). The lava lobe can be divided into the upper flow crust (abundant vesicle development), flow interior (sparse vesicle development), lower flow crust (pipe vesicle development). Among them, the top zone is the main reservoir location in lava flow, and the thickness of the top pore zone, which occurs between 0.5 m and 39 m, changes in relation, and accounts for 6%–23% of the total thickness of the lava flow unit, and has a porosity of up to 35% (Huang et al., 2010; Yi et al., 2015; Tang et al., 2017a, 2017b). Lava flows are widely distributed in the Junggar, Santanghu, Songliao, Erlian and Bohai Bay basins where basic, intermediate and acidic lava flows are found (Nie et al., 2009; Du et al., 2012; Ji et al., 2012; Zhang et al., 2013a, 2013b, 2013c; Liu, 2015; Planke et al., 2017; Dai et al., 2019; Yang, 2021). The statistical results of cores and outcrops indicate that the vesicle of acidic lava flows in the Songliao and Hailar basins developed within 30 m of the top, and that basic lava flows developed at 2–15 m from the top. If the type of lava flow is subdivided, the ratio of the favorable reservoir thickness to the total thickness of the medium-basic braided lava flow is higher than that of the simple lava flow (Fig. 8f, g). The vesicle layer of the simple lava flow has good extendibility in the lateral, and the vesicle layer of the braided lava flow can form a reticular connective body through the cross overlap of the lava lobe (Fig. 8d).

(2) **Lava dome** Lava domes are mounds of viscous lava and rocks that pile up and accumulate around a volcanic vent (Cas and Wright, 1987; Fink, 1990; Sigurdsson, 1999). They form as magma cools and degasses relatively quickly after erupting onto the Earth's surface (Fink, 1990; Calder et al., 2015). They are also known as "dome shaped volcanoes", "bell volcanoes", " volcanic domes" and "lava cones". Due to the high viscosity and poor fluidity of the molten magma, the lava is extruded from the overflow outlet and expands in all directions, and piles up in the vicinity of the crater, forming a dome-shaped hill with a relatively large vertical to horizontal ratio (Fig. 8e). Andesite, dacite, rhyolite, trachyte and phonolite are the most common rock types. While vesicles are not developed, shrinkage fractures such as "suture-like fractures" and columnar joints are developed. The thickness of favorable reservoirs of the trachytic lava dome of the Xujiaweizi fault depression in Songliao Basin is up to 70–200 m. The ratio of the favorable reservoir thickness to the total thickness of the lava dome accounts for 7%–60% (Fig. 8h-i) (Huang et al., 2010). The reservoirs of the dacite lava dome in the Dehui Fault depression only occur at the top, within a thickness of about 70 m, and the ratio of reservoir thickness to unit thickness is small (Tang et al., 2018). The basaltic dome of the Paleogene in Yitong Basin in Jilin Province reveals that the reservoirs are only distributed within a range of 60 m at the top (Tang et al., 2020a). The average porosity of the lava dome in the Dehui fault depression and Yitong Basin is 7.6% and 5.0%, respectively. The porosity values of lava domes are usually less than those of lava flows.

#### 4.2.2. *Relationship between volcanic edifice and reservoir*

**Edifice** The constructional mass of a volcano (Davidson and De Silva, 2000). A volcanic edifice is the overall combination of the products of a volcano, including volcanic cones above the ground and volcanic channels formed by the interpenetration of magma underground (Walker, 1986; Sigurdsson, 1999; Serrano, 2002). Considering the unification of strata occurrence variation and correlation of the rock layer, the volcanic edifice is defined as all of the products that come from one eruptive vent that overlap and form the volcanic body (Sigurdsson, 1999; Tang et al., 2007); the time span for building a volcanic edifice varies from a few months to hundreds of thousands of years. The volcanic edifice is mainly limited by the eruption interval unconformity boundary, and there could be some short time eruptive intervals between the deposited units. The research on the relationship between volcanic edifice and reservoir mainly focuses on two aspects: type of volcanic edifice vs. reservoir, and facies belt of volcanic edifice vs. reservoir.

*4.2.2.1. The relationship between volcanic edifice type and reservoir.* Depending on the rock composition, volcanic edifices can be divided into lava, composite and pyroclastic volcanic edifices. Based on the chemical composition of the rock, they can be divided into basic, intermediate and acidic volcanic edifices (Chen et al., 2000; Hunag et al., 2007; Tang et al., 2012). Based on the stratigraphic structure, they can be divided into pseudo stratification, stratification and massive volcanic edifices (McPhie et al., 1993; Yamamoto et al., 2005; Tang et al., 2011). Based on the shape, they can be divided into shield like, mound like, cone like and dome volcanic edifices (Borgia and Treves, 1992; Serrano, 2002; Tang et al., 2017a, 2017b).

As evidenced from wells that have been drilled in basins, the volcanic edifices may be classified according to their rock composition. The field results show that the reservoir thickness of acidic pyroclastic volcanic edifices is stable laterally, and the edifice shape is of a plate or sheet. The reservoir thickness of acidic compound volcanic edifices and lava volcanic edifices is unstable laterally, and the shape of the edifice is of a mound shape and sheet shape, respectively. The reservoir thickness of intermediate-basic lava volcanic edifices is unstable, and the edifice shape is of a mound or wedge (Tang et al., 2012). In the Sangliao Basin, the porosity values of polygenetic volcanic edifices are higher than those of monogenetic volcanic edifices (Li et al., 2000).

*4.2.2.2. The relationship between the facies belt of the volcanic edifice and reservoirs.* Although various schemes have been developed for the division of facies belts on a volcanic edifice. The volcanic edifice is generally divided into three facies belts according to the lithology, lithofacies and dip characteristics: crater-near crater facies belts (central facies belts), proximal facies belts (middle facies belts) and distal facies belts (Cas and Wright, 1987; Sigurdsson, 1999; Tang et al., 2008; Hou, 2011; Wang and Chen, 2015). Each facies belt has specific characteristics of lithology, dip, reservoir and reservoir origin (Table 2): the crater-near crater facies belt has characteristics of thick layers, steep dip, disorderly overlapping and large pyroclastic particles; the distal facies belt has characteristics of thin layers, gentle dip, distinctive overlapping and small pyroclastic particles; and the characteristics of the proximal facies belt fall between these two types. Drilling efforts have revealed that the central facies zone of the volcanic edifice is the main target for favorable reservoirs and oil and gas accumulation. This is the general principle for volcanic edifices in basins such as Songliao Basin (Fig. 9), Hailar, Junggar Basin and Bohai Bay (Li, 2012; Sun et al., 2013; Wang and Chen, 2015; Liu et al., 2016a, 2016b; Zhang et al., 2018a, 2018b; Yu, 2019; Zhu et al., 2020b; Huang et al., 2021; Meng et al., 2021). Crater-near crater facies belts have high porosity and permeability values, large pore throat radii, well-sorted throats and medium-positive skewness. Proximal facies belts have low porosity and permeability values, small pore throat radii, poor-sorted throats and medium skewness (Fig. 10a–f) (Tang et al., 2008).

#### 4.2.3. *Relationship between eruptive interval unconformity/tectonic unconformity boundary and reservoir*

The volcanostratigraphic boundary can be divided into eruptive

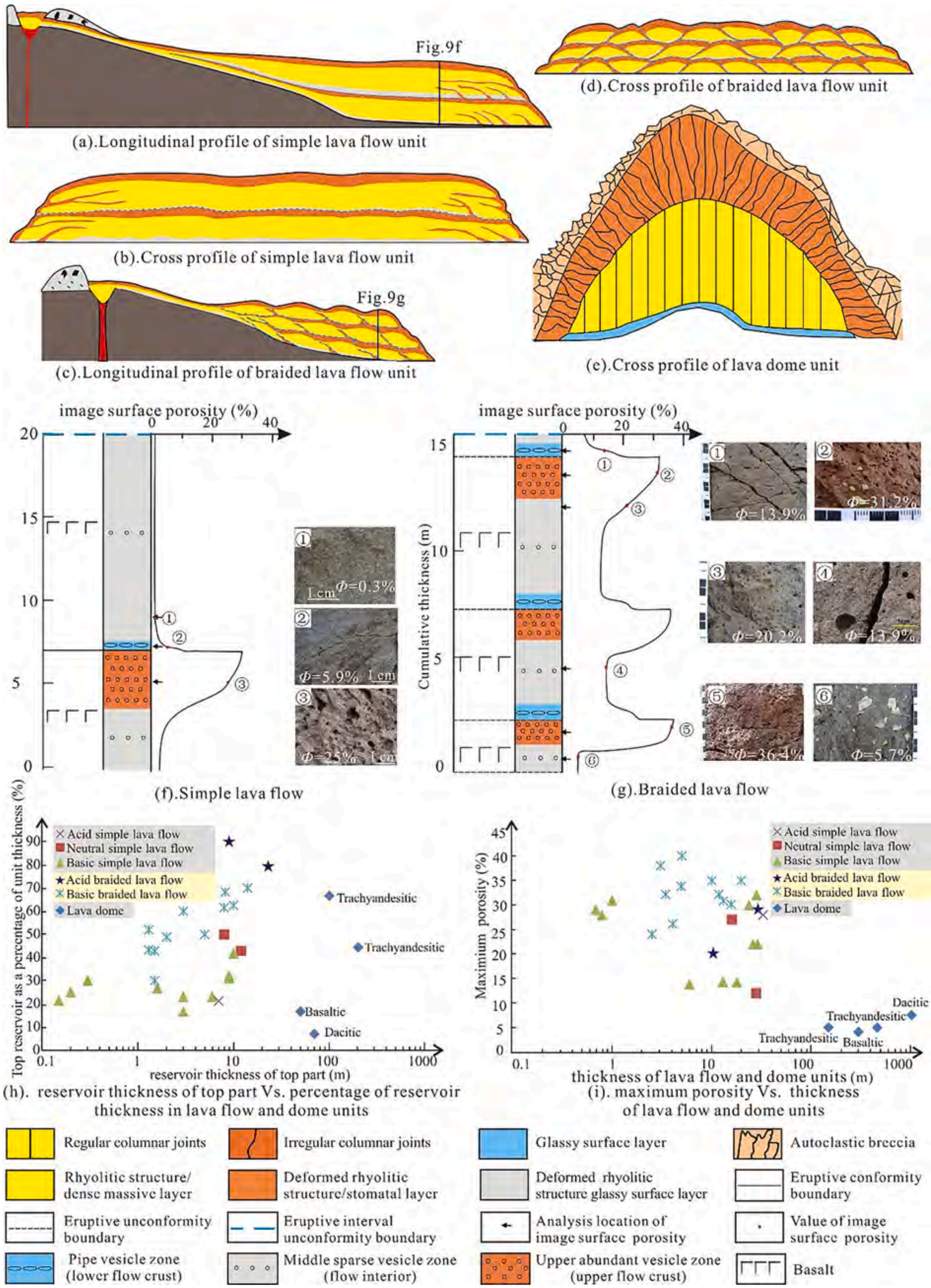


**Fig. 8.** (a–e) Sketches of the facies architecture and (f–i) reservoir characteristics of the lava flows and the lava domes. a-e: from Tang et al. (2017a, 2017b), f-g: from Tang et al. (2013).

**Table 2**
Belts and reservoir characteristics of the volcanic edifices.

| Volcanic edifice belt | | Crater-Near crater belt | Proximal belt | Distal belt |
|---|---|---|---|---|
| Typical lithology types | | crypto-explosive breccia, perlite, pillow lava, welded agglomerate/breccia | welded lapillistone\tuff, lava | sedimentary pyroclastic rocks, tuff, vitreous clastic rocks |
| Typical lithologic fabric | Rhyolite structure | steep angle/strong deformation | medium-gentle angle/weak deformation | small amount of lava |
| | Vesicle-amygdale geometry | rounded, elliptical | tubular, elliptical, rounded | a few pores |
| | Welded texture | strong | weak | none |
| | Bedding | massive bedding | wave bedding, massive bedding, graded bedding, cross bedding | horizontal bedding, parallel bedding |
| | Grain size of particle | breccia/lapilli | lapilli/tuff | tuff/tuffite |
| Types of stratigraphic units | | braided lava flow/simple lava flow (thick layer)/lava dome/pyroclastic flow | simple lava flow (thin layer)/base surge | air fall/volcaniclastic apron/volcanic debris flow/lahar |
| Overlap of stratigraphic units | | disorderly | disorderly-orderly | orderly |
| Dip angle of outcrop formation | | 40°–70° (present)/15°–35° (original) | 30°–45° (present)/5°–25° (original) | 25°–30° (present)/0°–5° (original) |
| Shape | | dome-like, mound-like, shield-like | wedge-like and plate-like | plate-like and sheet-like |
| Main reservoir space | Vesicle/amygdale | abundant | a few | a few |
| | Intergranular pores | macropores | mesopores | pinholes |
| | Dissolution pores | moldic pores, sieve pores, micropores | sieve pores, micropores | micropores |
| | Crypto-explosive cracks | abundant | a few | none |
| | Tectonic fractures | concentric radial fractures, high density | medium density | regular stress joints, low density |
| | Devitrified micropores | no significant difference | | |
| Weathering before burial | | strong | medium | weak |
| Petrophysical properties | | medium porosity and high permeability reservoir, locally high porosity and high permeability reservoir, large pore throat radius and good sorting | medium porosity and medium permeability reservoir, locally medium porosity and high permeability, large pore throat radius and good sorting | low porosity, low permeability, small pore throat radius, poor sorting |

Note: This table is modified from the literature, and the data are mainly based on the Mesozoic volcanic rocks in the Songliao Basin and its adjacent area in Northeastern China.

conformity, eruptive unconformity, eruptive interval unconformity and tectonic unconformity boundaries (Salvador, 1987; Rita et al., 1997; Corsaro et al., 2002; Tang et al., 2013; Tang et al., 2015). The development of secondary pores in volcanic rocks is closely related to fluid pathway; the eruptive interval uncomformity boundary and tectonic unconformity boundary in the volcanostratigraphic boundary system can indicate the fluid active area for the open system when exposed and the fluid migration pathway when buried. Thus, these two kinds of boundaries are closely related to the spatial distribution of secondary porosity.

(1) **Eruptive interval unconformity boundary** refers to the contact relationship between the overlying rock and the volcanic rock after erosion or denudation during the eruption interval (generally decades to thousands of years). This kind of boundary, in the horizontal direction, has combinatorial features of weathered crust (relatively positive terrain) and tuffite or sedimentary rocks (relatively negative terrain) with lithics of underlying pre-existing rock.

(2) **Tectonic unconformity boundary** refers to the contact relationship between the volcanic rocks within the basin or sub-tectonic units after overall uplift denudation or differential burial, and the overlying stratum. When the structure is uplifted, the volcanic rocks undergo long-term denudation and planation, and weathered crust with wide distribution and relatively flat morphology is developed. The scale of weathered crust and

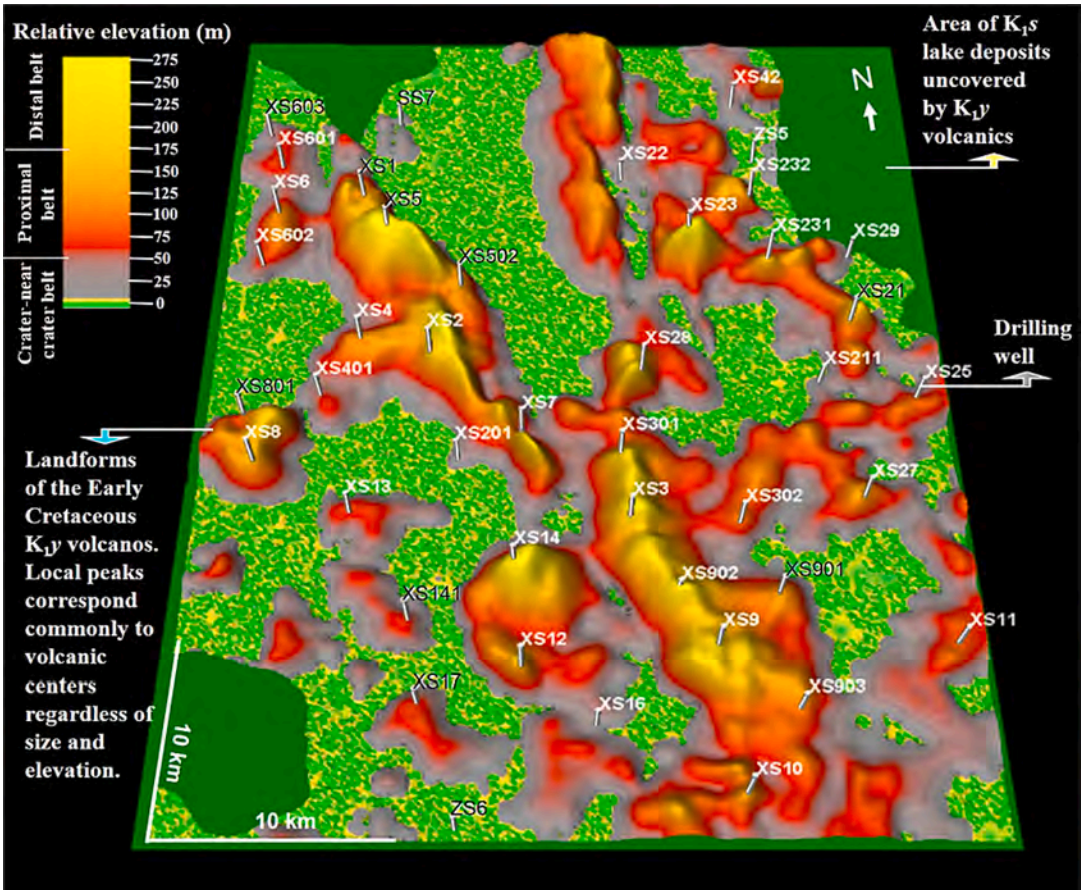


**Fig. 9.** Three-dimensional map of the buried volcanos in the Xujiaweizi graben, Songliao Basin, China (from Wang and Chen, 2015).

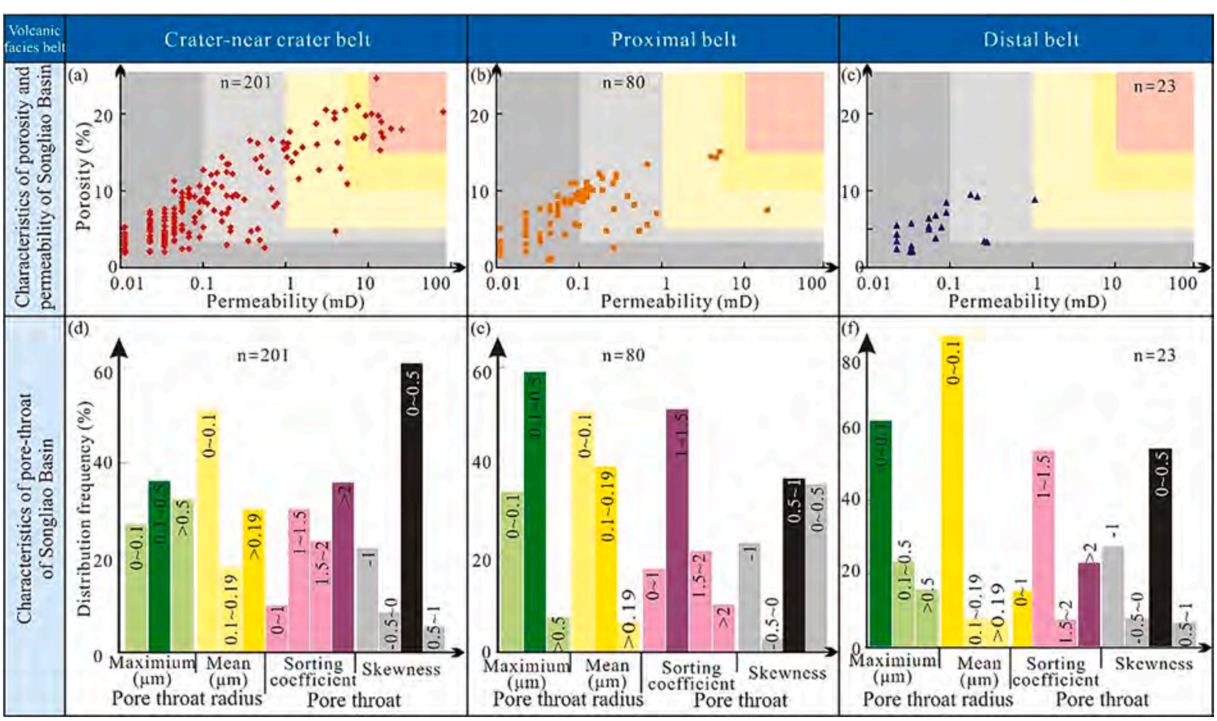


**Fig. 10.** Relationship between the volcanic edifice belt and the porosity-permeability in the Songliao Basin, China.
Notes: the data for the Cretaceous volcanic rocks in the Songliao Basin are based on the data reported by Tang et al. (2008).

sedimentary rocks is often larger than that of eruptive interval unconformity.

The weathered crust under the eruptive interval unconformity and tectonic unconformity boundaries has stratification characteristics (Fig. 11a), and from top to bottom it can be divided into the soil layer, hydrolysis zone, dissolution zone, disintegration zone and parent rock layer. The hydrolytic zone and dissolution zone are the favorable targets for reservoir development. Drilling efforts have revealed that most favorable reservoirs are distributed in the range of 200 m below the eruption disconformity and structural unconformity boundary, and in a few cases, they can extend down to 500 m. There are differences in the depth of the distribution range between basins, different blocks within the same basin, and between different wells within the same block (Fig. 11b). Studies have shown that the favorable reservoirs below the eruptive interval unconformity and tectonic unconformity boundaries in the Junggar, Hailar and Songliao basins are zonal (Cui et al., 2016; Zhao et al., 2016; Ma et al., 2019a, 2019b). The thickness and vertical distribution range of favorable reservoirs are controlled by many factors. For example, in the paleogeomorphic zone of weathered crust, the residual hill and its marginal zone are better than the gentle slope zone, channel and depression zone (Fan et al., 2017). Lithologic and lithofacies characteristics are also important factors affecting the distribution range of reservoirs. For example, if the rock under the unconformity boundary of Carboniferous in the Dixi area of Junggar is pyroclastic rock, it can extend to 400 m below the boundary, and it can extend to 250 m below the boundary if it is lava (Chen et al., 2016a, 2016b). The existence of fault zones can also enlarge the range of influence of weathering (Wang et al., 2011a, 2011b).

Favorable reservoir development also promotes the accumulation of oil and gas. As revealed by drilling efforts, most of the oil/gas/gas-water/oil-water plays are within 150 m below the eruptive interval unconformity boundary and tectonic unconformity boundary (Fig. 12a), and the oil/gas/oil-gas plays are more concentrated in the 100 m range (Fig. 12b); thus, this depth segment is an important zone for oil and gas exploration.

## 5. Reservoir origin

The main factors that play a role in reservoir construction are primary volatile release, condensing shrinkage, explosion and clastic particle support, as well as secondary recrystallization, tectonic activity, atmospheric water-formation and water-deep hydrothermal dissolution (Zhao, 1996; Guo et al., 1997; Liu et al., 2003; Gao et al., 2007; Luo et al., 2013). Filling, compaction and cementation are the main factors that damage the reservoir (Qiu et al., 2000; Dobson et al., 2003). This manuscript mainly introduces diagenesis that plays a role in reservoir construction.

### 5.1. Released and frozen volatiles

When molten lava ascends from the magma chamber, it contains volatile components, such as water, carbon dioxide, fluorine and chlorine (Wallace et al., 1995; Bachmann et al., 2009), and can also contain a small amount of He or Ar (Colin et al., 2013). When the magma pressure drops, gas bubbles escape from the molten lava. The bubbles expand and cohere during the ascending stage of molten lava (Lovejoy et al., 2004), and the bubbles are frozen by the lava when it solidifies and form vesicles. Volatiles are released over two stages, the ascending stage in the volcanic conduct and the flowing stage in the subaerial environment. The former can be seen as an approximate isothermal decompressional process, which is the main stage of vesicle formation. The latter is an approximate isobaric cooling process during which the vesicles are only adjusted in shape and distribution compared with the previous stage, and almost no new vesicles are generated (Fig. 13a).

Vesicles usually accumulate at the top part of lava flows. This phenomenon enhances the spatial distribution of good reservoirs in the upper part and poor reservoirs in the lower part. This spatial distribution becomes apparent when basaltic lava flows are thicker than 3 m (Bondre, 2003). In addition, when lava flows through areas of the underlying wet environment, squeezing action and the baking effect cause water to discharge and become volatile matter (Lockwood and Hazlett, 2010). When water and magma reach an appropriate proportion, the volatile matter is captured by the quickly cooling magma, forming vesicles. The vesicles only occur in the lower part of the lava flow. The spatial distribution of rhyolite lava flow in the Huoshiling formation of the Wangfu fault depression in Songliao Basin, China, has good reservoirs in the lower part and poor reservoirs in the upper part (Tang et al., 2016b; Wu et al., 2021). This may be the reason for the spattered cone of the Huoshao Mountain of the Wudalianchi volcanoes (Gao et al., 2010). When the vesicle is filled, it becomes an amygdale, which is most common in the basic lavas. The amygdales of basalt in the Songliao

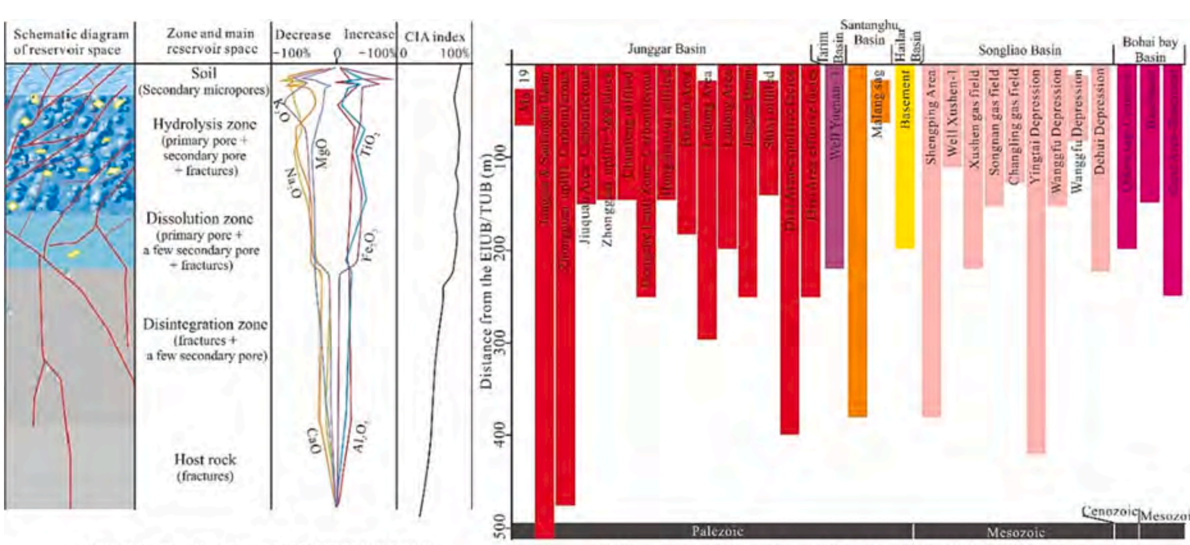


**Fig. 11.** Relationship between the eruptive interval unconformable boundary-tectonic unconformable boundary and the reservoir in the volcanic rocks in China's basins (Tang et al., 2020b).
Notes: a) CIA = $\{(Al_2O_3)/[(Al_2O_3) + (CaO^*) + (Na_2O) + (K_2O)]\} \times 100$. All of the principal components refer to mole fractions. CaO* is only for silicates.

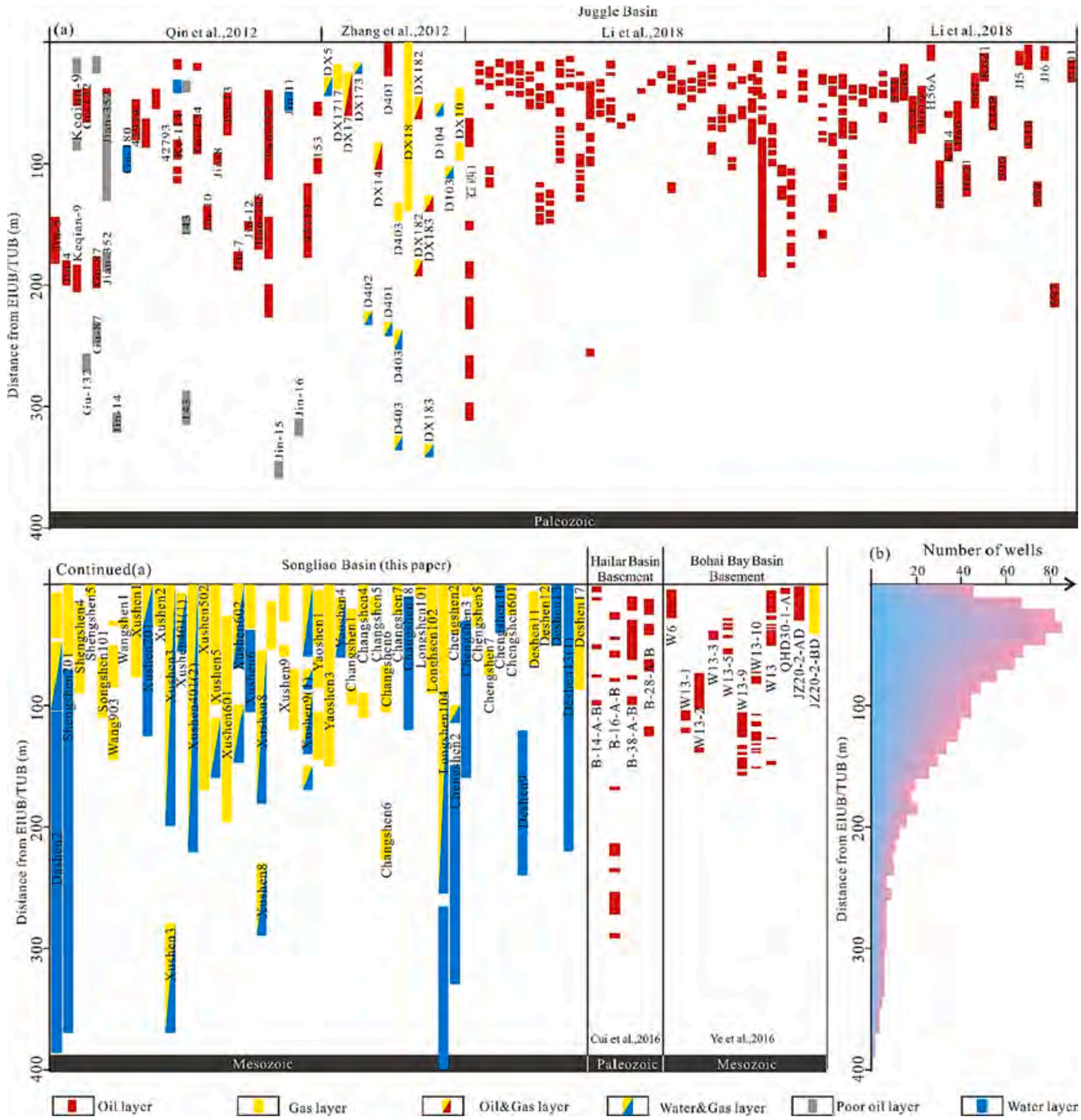


**Fig. 12.** Relationship between the eruptive interval unconformable boundary-tectonic unconformable boundary and the oil-gas in China's basins. (a) Characteristics of oil, gas and water under the eruptive interval unconformity boundary (EIUB)/tectonic unconformity boundary (TUB) of wells in basins; (b) Number of wells drilled in volcanic rock.

Note: the data are from the references (Qin et al., 2012; Zhang et al., 2013a, 2013b, 2013c; Cui et al., 2016; Ye et al., 2016; Li et al., 2018a, 2018b).

Basin underwent two types of filling, namely single component and composite component filling (Liu et al., 2010a, 2010b). The single-component amygdala can completely or partially fill the primary pores and greatly reduce the reservoir space. The composite component amygdala was formed by vitreous devitrification and alteration. When the volume of the rock skeleton remains constant, the composite component amygdala will increase the rock porosity.

Vesicle formation is in accordance with the coherence-diffusion-decompression model, and there is a nonlinear inverse relationship between the vesicle number density and vesicle volume in pumice (Gaonac'h et al., 2004). The development of vesicles is closely related to the volatiles contained in the magma. When the water content of rhyolites is low, the variation in water content will cause dramatic changes in the vesicle number (Blower et al., 2001). The bubble size, shape and distribution style have a significant effect on the permeability value (Mueller et al., 2005). The larger the porosity value, the smaller the compressive strength of vesicle lava, and a larger vesicle diameter means less compressive strength (Heap et al., 2014).

### 5.2. Explosion

There are three types of explosions. First, the expansion process of decreasing pressure during the magma ascending process causes phenocryst fragmentation. This can break the crystal and generate a crack, such as an irregular crack in quartz (Fig. 2e) or a crack along the cleavage of feldspar, hornblende or pyroxene and a small number of irregular cracks obliquely crossing the cleavage. Second, when the gas expansive force at a resulting ΔP at the magma-atmosphere interface is higher than the tensile strength of the matrix skeleton, fragmentation occurs (McBirney, 1973). A large number of pyroclastic particles are generated, and some particles preserve the explosive fractures. Third, volatile magma explodes in shallow depths (Fig. 13b, c). A hydrothermal explosion in shallow depth causes the country rocks to break and form tree-branch like fractures (Fig. 2m). This could have formed favorable reservoirs in the Songliao and Liaohe basins (Gu et al., 2002).

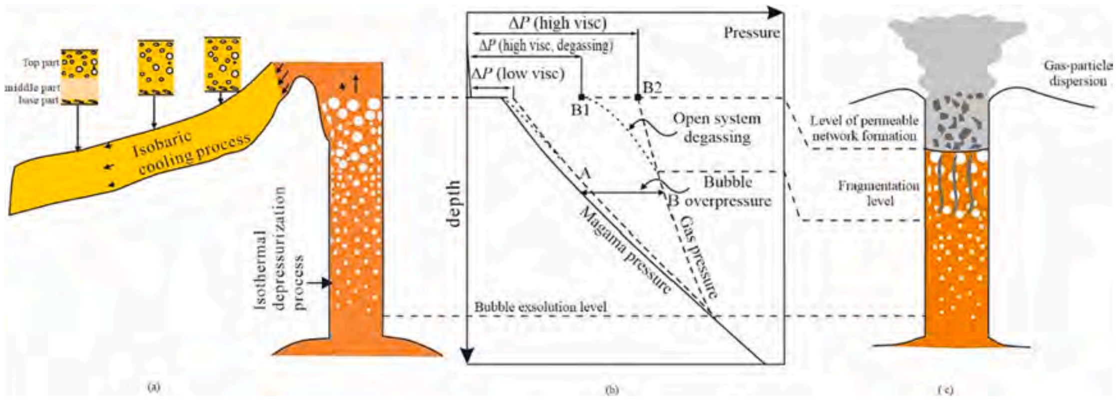


**Fig. 13.** Schematic diagrams of (a) vesicle evolution, (b) pressure evolution within a conduit, and (c) eruptive fracture formation.
Notes: If the magma viscosity is low (A), bubbles can freely expand to balance the ascent-driven decompression; so, the pressure difference between the magma (solid line) and the gas phase (dashed line) remains small, whereas for high magma viscosities (B), bubble expansion is hindered, and the bubble overpressure increases with ascent. If the force of the gas expansion due to the ΔP at the magma-atmosphere interface is greater than the tensile strength of the matrix skeleton, fragmentation occurs. Open-system degassing (dotted lines) may considerably decrease the ΔP (B1 instead of B2). Diagram b) was modified from McBirney (1973).

### 5.3. Condensation shrinkage

Generally, condensation shrinkage refers to the cooling process when the lava is in contact with relatively low temperature surrounding rock, air and water when magma ascends in the conduit and lava flows on the surface. The solidification stage of lava is a cooling process. The volume of lava shrinks, resulting in tensile stress, which can generate fractures. The fracture types are closely related to the cooling rate. First, the moderate cooling rate of lava flow (moving rapidly on land) generates autoclastic breccia fractures at the top part and platy joints at the lower part. Second, the slow cooling rate of lava flow (moving slowly on land) can generate the steeply macro-tortoise shell joints and irregular micro-tortoise shell joints (Conway et al., 2015). Third, the very slow cooling rate of lava flow or lava dome (ceased or moving very slowly on ground or in hypabyssal or ultra-hypabyssal conduit) can generate regular columnar joints in the lower part and irregular columnar joints in the upper part (Fig. 14). Fourth, the fast cooling rate of lava flow (contact with water body, such as liquid water, or snow) can generate concentric and radial joints (Bear and Cas, 2007). Subaqueous volcanic rocks are common in China's basins, such as the Junger Basin and Santanghu Basin (Mao et al., 2012; Zhu et al., 2012). These types of fractures likely exist in lava flows in these basins and should have good permeability.

The perlite/pitchstone/obsidian dome in the Songliao Basin has typical perlitic fractures, comprising arcuate, overlapping and intersecting cracks. This might be the favorable reservoir in the Songliao Basin (Wang et al., 2003a, 2003b). In addition, in the Huoshiling formation of the Wangfu fault depression, quenching fractures have developed at the bottom of rhyolite in a shallow lake environment (Tang et al., 2016b). Special fracture assemblages occur in specific locations, such as assemblages of columnar joints, concentric joints and radial

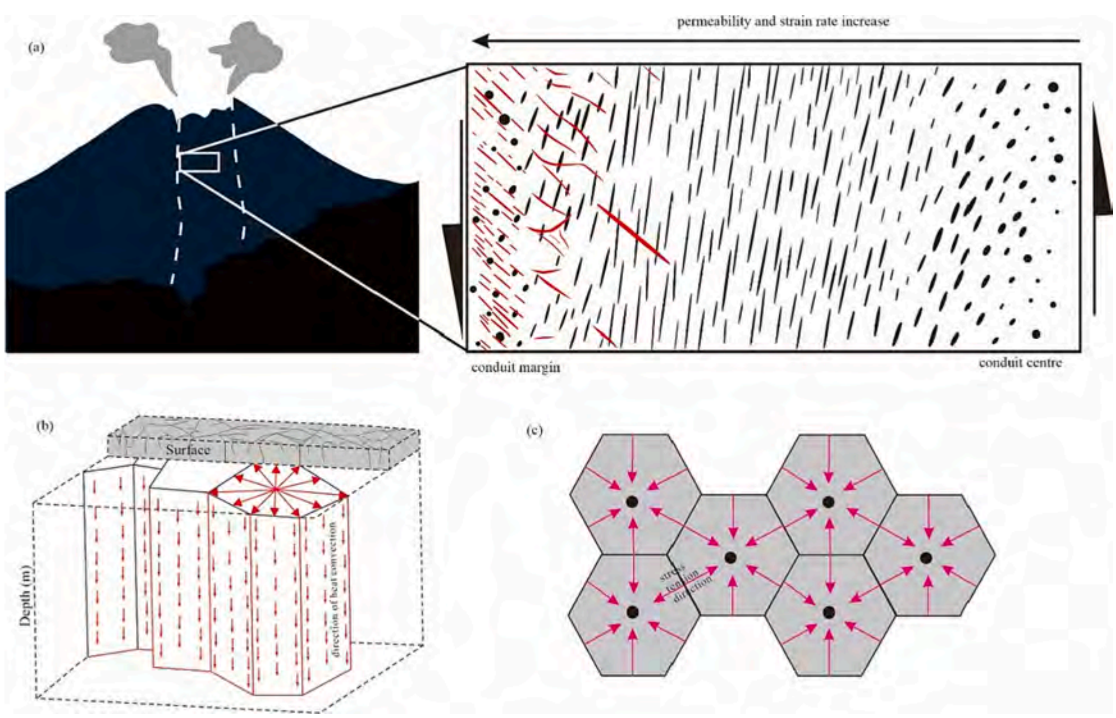


**Fig. 14.** (a) Schematic diagram of the fracture network near the conduit margins (Kushnir et al., 2017). The shrinkage fractures are produced in the lava with porosity development. (b) Heat-dissipative convection stage. The arrow represents the direction of convection (Budkewitsch and Robin, 1994). (c) The condensation shrinkage stage. The arrow's direction represents the stress tension direction under density equalization (Wang et al., 1991).

joints in lava tubes (Single and Jerram, 2004; Yi et al., 2016).

### 5.4. Particle supporting

Pyroclastic particles are produced during magma fragmentation. These particles are divided into breccias, lapillus and tuffs according to size (Fisher and Schmincke, 1984). In general, pyroclastic rocks in the crater-near crater belt have the characteristics of angular, poorly sorted and massive structure. Pyroclastic rocks in the distal belt have the characteristics of subangular-angular, moderately-well sorted and graded bedding. The relatively coarse particles can first form a stable skeleton, which plays two roles in the reservoir origin. First, intergranular pores can be formed because of no filling or the low filling degree. Second, the coarse granular skeleton reduces the damage of primary intergranular pores and secondary dissolution pores during the burial process (Klug and Cashman, 1996). With respect to a supporting role, the lithics of lava are probably more stable than the lithics of pyroclastic rocks because pyroclastic rocks contain volcanic ash that will soften during contact with water. When the pyroclastic rocks are buried, the granular framework can protect the intergranular pores, but as the static pressure of the overburden increases gradually, the contact relationship of particles changes from point contact to line contact, and the intergranular pores suffer serious damage. The supporting role may play a greater role at the shallow burial depth, but the effect of this role is limited at the deep burial depth. The surface porosity of residual intergranular pores is about 1.8–5% in line–suture contact rocks with intensive mechanical compaction (Tang et al., 2016a). Therefore, particle supporting plays an important role in preserving pores for pyroclastic rocks and tuffite.

### 5.5. Tectonism

Tectonic fractures form under tectonic stress and can be developed in dense lava, ignimbrite and pyroclastic rocks. Generally, shear fractures with steep angles, straight planes, far extension, orientation and groups are generated by shear stress. Conjugate joints are a good example of this kind of fracture. Stratification paralleling the axial fold occur in the folded strata. The Junger, Santanghu and Tarim basins have numerous large-scale overthrust structural belts and likely contain abundant seratifications in the volcanic rocks of the overthrust belts. The main origin age of the fracture is the Hercynian period (Fan et al., 2012). The Songliao and Hailer basins underwent inverse tectonic activities in the late Cretaceous when the seratifications and conjugate joints could have been generated. In the Liaohe and Bohai Bay basins, Meso-Cenozoic strike slip fault systems have developed, and tensional shear stress fractures can also form.

Under the tensile structural stress, the rocks are broken to form a mesh, forming an irregular and well connected tensile tectonic fracture. The fault depression period experienced in the eastern Chinese basin may have promoted the formation of such fractures, which are more developed in the hanging walls of faults with obvious stress disturbance action (Liu et al., 2016a, 2016b), and the linear density of fractures is inversely proportional to the distance from main faults, which also has a constraining effect on hydrocarbon accumulation (Gong et al., 2017).

### 5.6. Weathering

There are two kinds of weathering, physical and chemical weathering, both of which can enhance existing secondary pore and fracture systems to improve reservoir quality. Physical weathering manifests as rock fractures, which are caused by temperature change and external force. The fracture development zone under the weathered crust is similar to the favorable reservoir development zone, and the fracture development zone can extend 250 m below the boundary (Yuan et al., 2011; Zhang et al., 2019a, 2019b). Most chemical weathering is characterized by leaching, mainly through mineral dissolution by meteoric water, lake water or sea water. Leaching during weathering can form large intragranular dissolved pores, moldic pores and reticulated dissolution pore-fracture systems in the matrix (Pan et al., 2013; Qu et al., 2014). The weathered crust is formed under the action of both physical and chemical weathering, and according to the characteristics of the weathered products, it can be divided into five zones: final decomposition product zone, hydrolysis zone, leaching zone, disintegration zone and unweathered zone (parent rock). The final decomposition zone of weathered crust of basic rocks mostly consists of clay minerals and carbonate minerals. In the hydrolysis zone, olivine iddingsitizes, plagioclase kaolinitizes and pyroxene chloritizes. The mineral changes in the leaching zone are similar to those in the hydrolysis zone, but the weathering intensity is weak. The disintegration zone mainly reflects physical weathering. In terms of material composition, the crust layers roughly correspond to the soil layer, hydrolysis zone, dissolution zone, disintegration zone and parent rock layer of the weathered crust of the Carboniferous Kalagang formation in Santanghu Basin (Hou et al., 2011; Wang et al., 2011a, 2011b). Weathered reservoirs are mainly distributed in the dissolution zone (leaching zone).

Weathering is very common in volcanic strata, because volcanic strata undergo ephemeral construction and long-term erosion. Because within a short period of time a large amount of ejecta accumulate within a limited spatial range, a local high point in the land inevitably forms, especially in the vicinity of the crater, which is a positive terrain of several hundred meters in height. It may take several Ma for the overlying sedimentary strata to cover the volcanic rocks, so volcanoes usually undergo weathering for a certain amount of time prior to burial. For example, the longest time that the trachyte andesite volcanic strata of the Huoshiling formation in the Wangfu fault depression underwent leaching prior to burial may have been as long as 35 Ma (Tang et al., 2020c). Lava can effectively preserve the dissolution pores formed in this stage, which is one of the significant differences between volcanic reservoir formation and sedimentary rock formation. In addition, the volcanic strata are exposed to the earth's surface under the influence of tectonic uplift after burial and subsequently suffer from physical weathering and leaching, as is the case for the Carboniferous-Permian volcanic rocks in the Junger and Santanghu basins, which underwent leaching after burial once or even twice (Dong et al., 2013; Luo, 2007). Mesozoic-Cenozoic volcanic rocks in the Bohai Bay Basin may have also undergone uplift followed by physical weathering and leaching after burial (Qu et al., 2016; Ye et al., 2016; Wang et al., 2020; Yue et al., 2020). The thickness of strata affected by physical weathering and leaching is closely related to the position of paleogeomorphologic features and the composition and structure of underlying rocks. The depth for weathering is likely deeper in the high part of the paleotopography. The abundant connected primary pores and fissures in the underlying strata can provide a good pathway for fluid migration into deeper layers (Chen et al., 2016a, 2016b; Fan et al., 2017; Li et al., 2017).

### 5.7. Burial dissolution or alteration

Burial dissolution/alteration requires two material bases, one is fluid and the other is soluble components. This involves two kinds of fluids, acidic and alkaline, which correspond to different soluble components. Most basins are dominated by acidic fluids, and alkaline fluids occur in a few cases. In general, fluids rich in organic acids and carbonic acid are produced in freshwater-brackish water sedimentary strata and coal-bearing strata during burial. In addition, the acidic fluid may also come from an inorganic $CO_2$ origin. For instance, the calcite filled in the pores of volcanic rock reservoirs in the Songliao Basin have recorded an inorganic $CO_2$ origin (Yu et al., 2012; Zhang, 2018). Laumontite filling and quartz dissolution occurred in the volcanic rocks of the Kalagang Formation in the Malang Sag, Santanghu Basin, indicating that the area experienced alteration by alkaline fluid (Liu et al., 2012).

Dark mudstone and coal seam are often developed in the strata of fault depression basins. According to the formation process of coal, there are two stages that produce a large amount of organic acids. In the first stage, plant remains buried at a depth of 200–400 m are transformed into peat and then lignite, and the pH value of the fluid reaches as low as 3.3–4.6 (Zheng and Ying, 1997). The second stage occurs when the temperature reaches 80–120 °C, and the pH value of the formation water is significantly reduced as organic acid material is discharged during the evolution of organic matter in the mudstone and coal seam. The soluble components can be dissolved again under acidic fluid (Zhang et al., 2011); a large amount of carbonic acid can also be produced when the temperature exceeds 120 °C. A large amount of acid soluble components such as olivine/pyroxene/hornblende/alkaline feldspar, as well as rock debris, volcanic glass and volcanic ash are developed in volcanic rocks, whose total content is much higher than normal arkose, lithic sandstone and quartz sandstone (Liu et al., 2007; Yu, 2019). This can also include turbidite and calcite precipitates under early alkaline conditions (Liu and Yu, 2010; Liang et al., 2011; Chen et al., 2013; Zhu et al., 2014), or plagioclase altered into laumontite during the weathering process (Luo, 2007). Burial dissolution can produce dissolution sieve like pores and micropores (Li et al., 2010; Gao et al., 2013; Li et al., 2014a, 2014b), and can also promote the formation of inner type reservoirs of volcanic weathered crust or improve the physical properties of reservoirs under the eruption of the discontinuous unconformity boundary (Huang et al., 2012). The dissolution characteristics can be defined according to parameters such as neutron porosity, measured formation resistivity and porosity calculated by density logging. The lithology index of altered reservoirs is smaller and the alteration index is larger, while the lithology index of unaltered reservoirs is larger and the alteration index is smaller (Wang et al., 2013a, 2013b).

### 5.8. Devitrification

Devitrification is the conversion of glass to crystalline material (Neuendorf et al., 2011). The vitreous composition in volcanic rock is unstable, because when the temperature and pressure increase due to burial, the vitreous material gradually transforms into crystalline material. After devitrification, acidic glasses often have felsic and spherulite structures (Fig. 2q) and Fe2O3 precipitates, while basic glasses often have cryptocrystalline structures and Fe2O3 precipitates. Using the principle and physical process and mass balance method of volcanic glass devitrification to estimate the pores generated by the devitrification of volcanic glass in spherulite rhyolite, welded tuff and tuff, the results show that the complete devitrification of rhyolitic glass forms feldspar and quartz spherules, which can produce $\geq$8.88% porosity (Zhao et al., 2009a, 2009b). For example, in the Xushen-1 well, the porosity of rhyolite can be increased by 2–5% (Liu et al., 2008). The significance of devitrification is that it can generate reservoir space connected by rock, which is also a unique phenomenon of volcanic rocks. Such pores are found in outcrop areas with good reservoir quality, are filled with crude oil (Tian et al., 2013; Zheng et al., 2018a; Zheng et al., 2018b), and are a good indicator for exploration.

### 5.9. The volcanic rock reservoir is the result of complex superposition of multiple geneses

The formation of a volcanic rock reservoir is the comprehensive result of the above-mentioned factors. The process can be divided into three stages, namely syneruptive stage, pre-burial weathering stage and burial dissolution stage (Cai et al., 2010; Mao et al., 2015; Meng et al., 2016; Tang et al., 2017a, 2017b; Sun et al., 2019). These stages can take place during the reaction between hydrothermal fluid (volcanic hydrothermal fluid in the syn-eruptive period and tectonic-thermal fluid in the later period) and rock. Some areas also undergo the processes of uplift denudation and reburial after burial (Luo et al., 2012; Zhang et al., 2015; Guo et al., 2017), which further complicates the evolution process of reservoir space. The primary pores, fractures and tectonic fractures formed in the first place provide pathways for fluid migration in rocks during the later period, controlling the development of secondary pores (Yang and Lan, 2012; Liu et al., 2016a, 2016b; Li et al., 2019;). Fractures play an important role in the formation of large porosity and fracture reservoirs (Yang et al., 2007), and steep fracture zones may control the vertical zonation of favorable reservoirs (Zhao et al., 2014).

The evolution of void space in volcanic rocks can be divided into two types, evolution from lava that formed by condensation and consolidation and evolution from pyroclastic rock that formed by compaction and consolidation. There are some differences between the two evolution processes; for example, the deformation of lava is smaller under compression, while the deformation of pyroclastic rocks is larger. Therefore, the diameter of pores in lava may decrease slightly with an increase in burial depth, while the amount and shape of pores remains stable. The moldic pores and sieve pores generated by dissolution are also perfectly preserved. When the burial depth of the pyroclastic rock increases, some particles may be broken because of the particles' contact relationship evolving from point to line, to suture contact. Displacement between the particles may occur to achieve a new support balance because of the change in stress between particles. Therefore, the diameter of intergranular pores in pyroclastic rocks will decrease significantly, and the number of pores will increase slightly. The dissolution pores that were produced in the pre-burial and early burial stages are difficult to preserve during the adjustment process of particle contact. Thus, dissolution diagenesis during the pre-burial and early burial stages contributes finitely to the total porosity (Fig. 15).

## 6. Possible future research

Based on the summary and discussion of current research results, further research urgently needed to be carried out in the next stage includes, but is not limited to, the following aspects.

### 6.1. Reservoir spatial distribution of volcanic stratigraphic unit

It has been found that the volcanic reservoir is influenced by lithology, lithofacies, volcanic edifice, volcanic stratigraphic boundary, stratigraphic structure, diagenesis and other factors, which to some extent promote the understanding of the volcanic reservoir distribution pattern. However, when it comes to unrevealed stratigraphic unit types, reservoir prediction results diverge from reality, for example, with respect to burial depth, thickness, layer amount and other attributes. Because the reservoir distribution pattern is not well understood from the perspective of formation genesis and stratigraphic unit, it is difficult to achieve a comprehensive understanding of the reservoir distribution pattern. In most cases, the reservoir prediction is more like "the blind men and the elephant". After depicting each oil and gas reservoir under the constraints of existing data, it may be thought that the reservoir distribution pattern is clear, but after the next drilling event, the existing distribution pattern may not be applicable. Just like with every organ of the elephant's body, the understanding of the ear is not suitable for understanding the other organs. Therefore, understanding each volcanic reservoir requires "crossing the river by feeling the stone", meaning that a lot of repetitive work is needed to complete the characterization of the reservoir.

In order to solve this problem, the reservoir prototype model based on the deposit unit of the volcanic stratum should be analyzed. Only when the reservoir distribution patterns of all basic stratigraphic units are clearly understood can the distribution laws of volcanic reservoirs be comprehensively understood. The reservoir research results can guide the volcanic hydrocarbon exploration of the basin by providing references for improving the efficiency of reservoir characterization. At present, the reservoir models of the subaerial lava flow unit and lava dome unit are relatively clear, but the reservoir models of other units such as pyroclastic flow, base surge, volcanic debris flow, volcaniclastic apron, avalanche and subaqueous lava flow still lack a three-dimensional quantitative understanding. It is necessary to strengthen

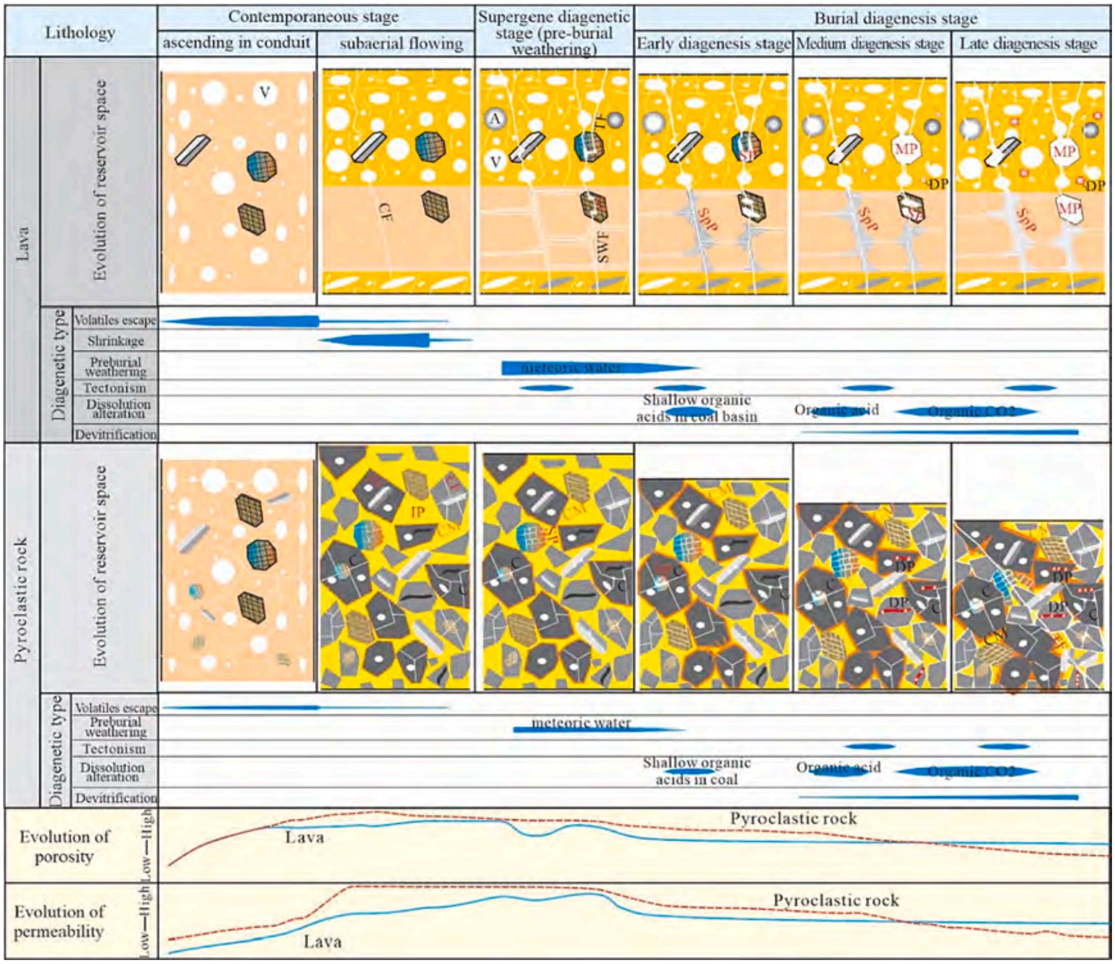

**Fig. 15.** Sketch map of the void space evolution in the volcanic rocks.
Notes: A-amygdales, DP-devitrified micropores, IP-intergranular pores, SpP-cavernous dissolution pores, SP-sieve-like dissolution pores, MP-moldic pores, V-vesicles, C-explosion cracks, CF-shrinkage fractures, TF-tectonic fractures, SWF-spherical weathering joints, and CM-cement.

the research on the reservoir prototype model of the above-mentioned stratigraphic units. For example, there are significant differences in facies structure between subaqueous volcanoes and subaerial volcanoes, and such units are widely developed in the Junger, Santanghu, Liaohe and Songliao basins (Mao et al., 2012; Zhu et al., 2012). Thus, the establishment of relevant prototype models is not only needed in practice but will also progress volcanic reservoir geological research.

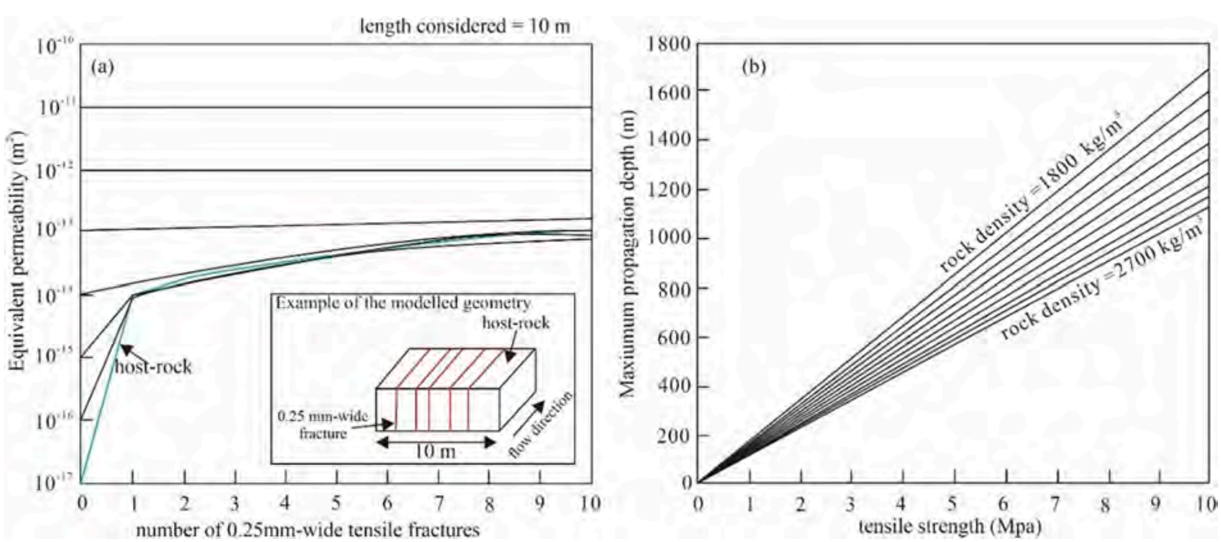

**Fig. 16.** Fracture permeability at different scales (Heap and Kennedy, 2016).

### 6.2. Fracture characterization of lava flow

Fractures are an important component of volcanic reservoirs and have attracted a lot of attention (Yuan et al., 2011; Dong et al., 2012; Wang et al., 2014; Liu et al., 2016a, 2016b; Ruz Ginouves et al., 2021). When high porosity samples contain microcracks, the improvement in rock permeability is not obvious (Lamur et al., 2017). When microcracks are contained in low-porosity samples, the permeability is usually 3–4 orders of magnitude higher than in the matrix part, though the microcracks in this part may have limited permeability relative to the entire volcanic layer. Rocks with different densities are subjected to different forces, resulting in different fracture strengths, while rocks with high densities have stronger tensile strength (Fig. 16) (Heap and Kennedy, 2016). It has been recognized that the eruption stage plays a crucial role in the formation of microcracks, and a large number of cracks can be formed during the lava cooling stage (Browning et al., 2016). In the process of lava flow, due to the differences in flow velocity caused by cooling, microcracks that are perpendicular to the flow can be generated at the outer part of the lava flow, resulting in connected channels among preexisting pores (Kushnir et al., 2017). Thus, microcracks can provide a good pathway for fluid migrating in the lava flow (Fig. 17). Therefore, the question of how to upscale from the plug sample to the whole strata also warrants an in-depth analysis, including matching field/core observations, laboratory test results, logarithmic interpretations and seismic predictions (Bischoff et al., 2017). At the same time, in describing the fractures of buried volcanic rocks, first-hand data come from the core, making it difficult to realize a comprehensive understanding of fractures due to the limitations in the core recovery ratio. Therefore, the description of the prototype model should be strengthened; the quantitative description of the formation process of primary fractures and the factors controlling the development of primary fractures should also be strengthened.

### 6.3. Quantitative research on reservoir genesis

In the study of volcanic rocks, the understanding of void space type and petrophysical properties is basically clear, while the reservoir distribution pattern is partially understood, and these aspects can effectively guide volcanic reservoir exploration and development (Wei et al., 2004; Zhou et al., 2006; Song et al., 2010; Qin et al., 2011; Gao et al., 2014). However, the understanding of reservoir formation and evolution lags far behind the above three aspects. At present, the analysis of reservoir genesis and the main controlling factors are only the expression of the comprehensive results of released and frozen volatiles buried in dissolution or alterations, which seriously hinders the in-depth understanding of volcanic reservoir geological theory. The formation and evolution of volcanic reservoirs in a basin can be divided into two stages: one being the stage of magma ascension and eruption and the other being the stage of post-eruption and burial. The former is the main stage that controls the development of primary pores and fractures. If lava with high volatile content ascends slowly and degasses, this may lead to the formation of lava flow; otherwise, a rapid rise may form pyroclastic flow, base surge or ash fall (Mueller et al., 2008). Due to the effect of surface tension, viscous lava with low volatile content accelerates solidification and avoids explosive eruption (Kennedy et al., 2016). Modern volcanoes reveal that the connectivity of primary pores is related to lithology and eruption mode (Colombier et al., 2017). The latter stage is the main stage of primary reservoir reconstruction and secondary reservoir formation. The study of reservoir evolution in the first stage is still in its infancy, which is mainly affected by experimental conditions. The research progress of the second stage is more in-depth than the first stage but is mostly a qualitative analysis, mainly because when primary and secondary pores are superimposed, it is difficult or nearly impossible to accurately separate the two contributions. At the same time, rock diagenesis experiments and simulations are lacking. In addition, the superposition of negative factors makes it difficult to quantitatively research the formation and evolution of volcanic reservoirs. However, in order to clarify the main factors controlling the

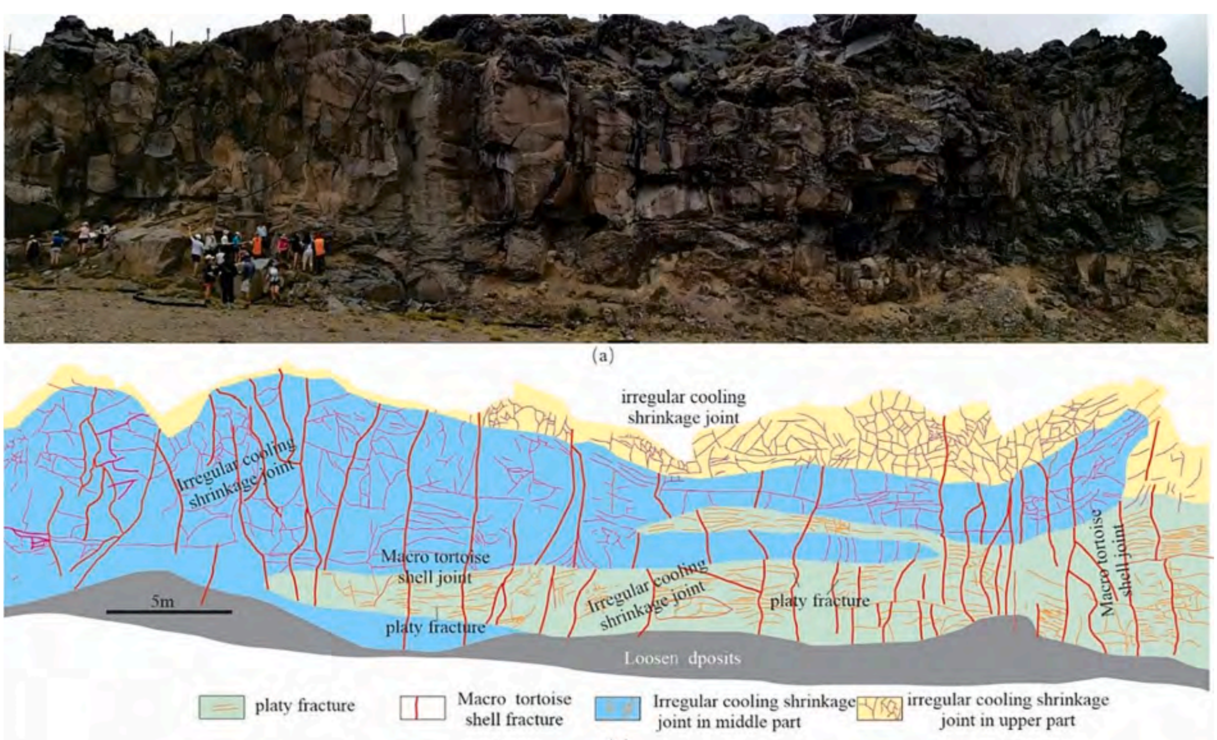


**Fig. 17.** The fracture system in an andesitic lava flow of the Pleistocene Whakapapa Iwikau Formation in Ruapehu Volcano, New Zealand. (a) Overview (taken by Marcos May Rossetti), and (b) interpretation of the fracture system.

formation of volcanic rock reservoirs, it is necessary to carry out a quantitative characterization of reservoir genesis. For example, the characterization of the weathered crust type reservoir requires quantitative or semi quantitative calculation of the contribution of pores formed by each genesis, so as to determine the real range of physical weathering and leaching.

## 7. Conclusions

(1) In volcanic rocks, the reservoir space can be divided into 11 types and 27 subtypes, including three types and five subtypes of primary pores, two types and nine subtypes of primary fractures, three types and seven subtypes of secondary pores and three types and six subtypes of secondary fractures. The primary pores are closely related to the phase structure, and the secondary pores are related to the primary pores and fractures. Overall, volcanic rock reservoirs are of medium-to-low porosity and medium-to-low permeability and thus can also be called tight reservoirs. Volcanic rocks have strong reservoir heterogeneity and a small porosity cutoff. The different combinations of reservoir space types have significant influence on the relationship between porosity and permeability.

(2) Volcanic reservoir formation correlates with burial depth. The porosity and permeability values of pyroclastic rock and tuffite above a depth of 3000 m (3 km) are higher than those of lava and welded pyroclastic rocks, while this trend is reversed below a depth of 3000 m (3 km). In general, many types of lithologies can bear hydrocarbons in a basin, but only certain lithologies can bear oil and/or gas within specific blocks. The distribution model of the reservoir correlates the volcanic stratigraphic units; for example, it identifies the "good upper flow crust and poor lower flow crust" pattern formed by the lava flow and lava dome and finds the porosity and permeability values in the lava flow to be higher than those in the lava dome. The porosity and permeability values of the crater and near crater belt of the volcanic edifices are better than those of the proximal belt and distal belt. Most favorable reservoirs are located within 200 m below the eruptive discontinuity unconformity boundary or tectonic unconformity boundary.

(3) Release of volatiles, cooling and quenching, pre-burial weathering and devitrification are the unique diagenetic processes that form volcanic rock. The deformation of lava during the compaction process is small, and that of pyroclastic rock is significant. The high content of unstable components in acidic fluid can provide the material for alteration and/or dissolution. The volcanic reservoir in a basin results from the above types of diagenetic processes and has a complicated origin process. The reservoir evolution process becomes more complicated when volcanic strata have undergone uplift and re-burial.

(4) With an increase in burial depth, the lava can preserve its original shape, which is beneficial to the preservation of vesicle, mold and sieve porosities. When the burial depth of pyroclastic rock increases, due to the increase in stress, displacement or crushing may occur between particles as they try to achieve a new support balance. Additionally, the diameter of intergranular pores probably decreases significantly, and the number of pores may increase slightly. The primary porosity and secondary porosity that is generated during eruptive, weathering and shallow buried stages can be damaged during the adjustment of particle support.

(5) At the moment, research on the characteristics and distribution pattern of volcanic reservoirs is at a quantitative level, while research on the reservoir origin is at a semi-qualitative level. The next stage of reservoir research should focus on the enhancement of the reservoir model based on volcanostratigraphic units and quantitative research on reservoir diagenesis.

## Declaration of Competing Interest

None.

## Data availability

No data was used for the research described in the article.

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