INTRODUCTION

With the continuously increasing global demand for hydrocarbon resources, reservoirs in volcanic rock are an important field of hydrocarbon exploration. More than 200 oil and gas fields have been found all over the world. The first oilfield in volcanic rock was found in the West Junggar Basin of China in 1957, and 14 reservoirs have been discovered, including Songliao Basin, Hailar Basin, Erlian Basin, and Santanghu Basin.¹ There are two types of the volcanic rock reservoirs in China. Native reservoirs rely on petrology, lithofacies, and diagenesis. Weathered profile reservoirs primarily rely on tectonic activity and weathering processes. Compared with native volcanic reservoirs, weathered profile reservoirs have better reservoir performance and production, and Kelameili and Niudong gasfield is the typical representative in China.² There are many weathered profile reservoirs in Junggar
Basin, and the volcanic rocks are widely distributed in the Carboniferous and Permian stratum, which were lifted entirely due to compression in the late Carboniferous. The native volcanic reservoir is mainly pore type and microfracture type. Compared with the native volcanic reservoir, the volcanic weathered profile reservoir has experienced a long-term weathering and leaching, forming the more abundant type of reservoir space, improving the pore space and seepage capacity, and is relatively easier to form favorable reservoir, higher and stable production. It has been proved in the process of exploration and development of volcanic reservoirs in China. Therefore, it is of great significance to study the reservoir characteristics, control factors, and genetic mechanism of volcanic weathered profile. In recent years, many scholars have carried out a lot of research on volcanic weathered reservoirs, mainly focusing on the structure of volcanic weathered profile, identification methods, reservoir development modes, reservoir control factors, and distribution rules, and have made remarkable achievements. However, for different types of the reservoirs, there are great differences in reservoir characteristics, main controlling factors, and pore mechanisms. Herein, taking the Carboniferous volcanic weathered profile in the northwestern Junggar Basin as an example, the formation of volcanic weathered profile is analyzed through the cores, geochemical analyses, thin-section analyses, geophysical interpretation, and production performances; then, the geological implications of volcanic weathered reservoirs is determined. The results will provide new guidance and geological support for future explorations of volcanic weathered reservoirs.

2 | GEOLOGICAL SETTING

The Junggar Basin is located in northern Xinjiang area of China and surrounded by the Paleozoic fold mountain system. Its northwestern area is West Junggar mountain, which includes Hala'alate mountain and Jayer Mountain. Tectonically, the West Junggar mountain is located on the intersection of the paleo-plates of Kazakhstan, Tarim, and

**FIGURE 1** Location and tectonic setting of the northwestern Junggar Basin. (A) Tectonic location of the study area; (B) the characteristic of tectonic profile.
Siberia, which were controlled by the evolution of the Paleo-Asian Ocean and surrounding orogen and experienced multiple tectonic movement.\textsuperscript{7,8} The ages of the volcanic rocks range from 340 to 320 Ma and 300 to 295 Ma; this is mainly during the Carboniferous period (359.98-299 Ma).\textsuperscript{9,10} The northwest Junggar Basin is located between the western Junggar folds system and the Junggar block, which includes the Wuxia fault, Kebai fault, Hongche fault, Zhongguai uplift, Chepaizi uplift, and the west slope of Mahu depression and Shawan depression (Figure 1A).\textsuperscript{11} It is characterized as having west-east zoning, north-south segmentation, and vertical stratification. Since the Carboniferous period, it has experienced the extension of the Hercynian period (416-257 Ma), the intensive extrusion thrust in the Indosinian period (257-205 Ma), the thrust superposition in the Yanshanian period (205-65.5 Ma), and the intracontinental movement in the Himalayan period (655.5-0 Ma). In general, it was tectonically active prior to the Yanshanian period and stabilized thereafter.\textsuperscript{12-14} It is NE spreading and has a length of 300 km and width of 20-30 km; it is described as a thin-crust nappe structure composed of the multiple lin- guiform slip blocks. It is hidden in the upper Jurassic and lies beneath the Cretaceous. The faults have a braided distribution on a plane and arc-extent. In A-B profile (Figure 1B), the fault is an imbricated structure with maximum fault displacement of 9-25 km. The strata of the upper and lower layers of the fault are quite different. The upper layer is relatively thin and lacks strata, and the lower layer is thick and has comprehensive strata, implying apparent syndeposition.\textsuperscript{15}

According to the outcropping strata of peripheral mountain system, and the drilling data, the Carboniferous northwest Junggar Basin is part of the Junggar hercynide fold base, where volcanism occurred in the Devonian and Carboniferous. Early Permian period. Fissure eruptions produced widespread volcanic rocks. The volcanic rocks were subject to intense weathering and leaching over the next 80 Ma, and then covered with overlying rocks.\textsuperscript{16} At this period of time, volcanic rocks were at the surface and submitted to weathering, which were also surely multiphase. Therefore, a regional unconformity is present between the Carboniferous and upper strata, which is conducive to the formation of volcanic weathered profile. The Carboniferous volcanic weathered profile is the main gas reservoir found to date.\textsuperscript{17} The thickness of sedimentary cap above Carboniferous basement in the northwestern margin of Junggar Basin is between 1500 and 3000 m, and the thickness of Carboniferous is between 1300 and 2000 m. The lithology is mainly basic eruption rock, neutral eruption rock, part of acid eruption rock, and metamorphic rock.

3 | MATERIALS AND METHODS

In this paper, core observation and description are carried out in 17 wells with a total of 1125 m and 60 samples taken. Seismic interpretation data were collected in the study area to predict natural fractures and the distribution of weathered profile. The main and trace element analysis of 12 core samples was carried out in State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Chengdu University of Technology).

Preparation of 0.03-mm-thick cast thin sheets for more than 40 samples from the northwestern Junggar Basin and microscopic studies of these thin sections were carried out using conventional lithofacies optical microscopy. At the same time, 100 ordinary thin slices and 210 cast thin slices were collected. Various types of pore spaces were evaluated by tissue observation and thin-section studies of resin-imregnated samples.

Petrophysical analysis was performed on more than 2000 porosity samples from 40 wells in the Six-nine, Zhongguai, and Hongche areas to measure the range of porosity and permeability. According to the requirements of China National Petroleum Industry Standard (SY/T 5521-2008), the porosity and permeability were measured using a CMS-300 automatic overburden hole penetrometer. The analyzer measures the porosity of the rock by the gas expansion method. The rock sample is pressurized and stabilized together with the helium gas, and then, the helium gas is expanded into a chamber of a known precise volume to stabilize the pressure again. The pore volumes at the beginning and end are calculated using Boyle’s law.

Many types of information on oil and gas exploration from Xinjiang Oilfield Company, PetroChina, including logging, mud logging, and oil and gas testing, were used for fine vertical evaluation of weathered profiles. Natural gamma ray (GR), spontaneous potential (SP), acoustic (AC) and shallow dual lateral resistivity logging (RS), the deep research of dual lateral resistivity (RD), microspheres focused resistivity (MSFL), density (DEN), borehole diameter (CAL), and compensated neutron log (CNL) explain the lithology and oil saturation data from geophysical method and also from Xinjiang Oilfield Company, PetroChina.

4 | RESULTS

4.1 | Volcanic rock formation environment

Based on the total alkali-silica (TAS) diagram, recommended by the International Union of Geological Science (IUGS) magmatic classification committee,\textsuperscript{18} the Carboniferous volcanic rock in the northwest Junggar Basin is dominated by calc-alkali volcanic rock.

The island arc is a long series of arc-shaped islands at the edge of the mainland, which is associated with strong volcanic, seismic, and orogenic processes. The oceanic lithosphere grows and expands from the mid-ocean ridge with
mantle convection, and forms island arc after subduction at the corresponding active continental margin. After the island arc volcanism, a variety of rock assemblages were formed, and the content of volcanic elements in different tectonic environments was different. Generally speaking, calc-alkaline basalt is the main volcanic rock of island arc, and Nb, Ta, and Ti are negatively abnormal. In order to determine the degree of alkalinity of volcanic rocks, the Rittmann index is generally adopted.

\[
\sigma = \left[ \omega \left( K_2O + Na_2O \right) \right] / \omega (SiO_2 - 43) \tag{1}
\]

If the Rittmann index is less than 3.3, it is calc-alkaline rock, 3.3-9 is alkaline rock, and >9 is called peralkaline rock. The Carboniferous volcanic rock contains 53.99%-76.04% of SiO₂ and 1.00%-8.12% of Na₂O+K₂O. The K₂O/Na₂O value is 0.01%-2.91%, and CaO value is 0.34%-15.56%, indicating that the rock is both relatively alkali-rich and calcium-rich, respectively (Figure 2). Among the trace elements, Rb, Nb, Ta, Sr, P, and Ti are depleted (Table 1), implying arc volcanic rock characteristics and the formation of an intraplate island arc environment.

### 4.2 Classification of the volcanic rock weathered profile structures

The formation and evolution of a weathered profile is determined by petrology, climate, unconformity, paleogeomorphology, and time. Since the 1990s, as research has deepened, weathered profiles have been divided into sedimentary cover, upper weathered profile, lower weathered profile, and compacted volcanic zone based on the relationship between porosity and depth. According to drilling core analyses, the weathered profile is divided into soil layers, hydrolyzation zone, leaching zone, disintegration zone I, disintegration zone II, and unweathered zone.

Based on observations of more than 40 drilling cores and 200 thin slices, considering weathering stratigraphy, oxide content at different depths, the volcanic weathered profile is divided into four zones from top to bottom: weathered clay zone, intensive weathered zone, weak weathered zone, and unweathered compacted zone (Figure 3). In the different structural layers, the oxide content is quite different.

![Figure 2](https://example.com/figure2.png)

**Figure 2** Silicon alkali map of Carboniferous volcanic rocks in the northwestern Junggar Basin.
Therefore, the weathered index was used to quantitatively classify different structural layers.  

\[ F_i = \sum \left( \frac{C_{\text{om}} - C_{\text{cm}}}{C_{\text{om}}} \right) \times 100\% \]  

(2)

where \( F_i \) is the weathered index; \( C_{\text{om}} \) is the main element content of parent rock, \%; \( C_{\text{cm}} \) is the content of main elements in weathered profile structure, \%.

Combined with the systematic analysis of the weathered profile structure of 15 wells in the study area, the weathered indexes of four structures of volcanic weathered profile are \( \geq 50\% \), 25%-50%, 10%-25%, and <10%, respectively. Controlled by alteration, from parent rock to soil layer, the content of Fe\(_2\)O\(_3\), Al\(_2\)O\(_3\), and other secondary minerals increased, Na\(_2\)O, K\(_2\)O, CaO, and other soluble minerals decreased, and the content of SiO\(_2\) in volcanic skeleton minerals decreased (Table 2). The weathered clay zone is located on the top area as fine-grain residues produced from weathering processes. It is characterized as purple gray and brown soil without bedding and is mainly distributed in the lower position and slope. The intensive weathered zone has characteristics...

### TABLE 1 Trace elements of Carboniferous volcanic rocks in the northwestern Junggar Basin

| Sampling area | Value type | La (10\(^{-6}\)) | Ce (10\(^{-6}\)) | Pr (10\(^{-6}\)) | Nd (10\(^{-6}\)) | Sm (10\(^{-6}\)) | Eu (10\(^{-6}\)) | Gd (10\(^{-6}\)) | Tb (10\(^{-6}\)) | Dy (10\(^{-6}\)) | Ho (10\(^{-6}\)) | Er (10\(^{-6}\)) |
|---------------|------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Zhongguai     | Min.       | 4.31             | 12.38            | 1.93             | 10.05            | 2.65             | 0.86             | 2.81             | 0.49             | 2.96             | 0.62             | 1.84             |
|               | Max.       | 42.78            | 91.44            | 10.29            | 40.42            | 7.55             | 1.89             | 7.75             | 1.00             | 5.47             | 1.17             | 3.43             |
|               | Av.        | 13.25            | 31.00            | 3.92             | 17.55            | 4.30             | 1.32             | 4.70             | 0.76             | 4.55             | 0.94             | 2.75             |
| Hongche       | Min.       | 14.77            | 35.02            | 4.17             | 18.00            | 4.05             | 1.02             | 4.06             | 0.62             | 3.67             | 0.75             | 2.27             |
|               | Max.       | 25.37            | 56.55            | 7.60             | 34.36            | 8.96             | 1.66             | 10.08            | 1.76             | 11.10            | 2.37             | 6.99             |
|               | Av.        | 20.34            | 49.21            | 6.16             | 26.53            | 6.14             | 1.35             | 6.58             | 1.06             | 6.41             | 1.33             | 4.01             |
| Six-nine      | Min.       | 8.15             | 19.36            | 2.62             | 11.87            | 2.75             | 1.11             | 3.15             | 0.50             | 3.08             | 0.66             | 1.99             |
|               | Max.       | 20.11            | 44.74            | 5.90             | 27.01            | 6.36             | 1.90             | 7.25             | 1.19             | 7.20             | 1.50             | 4.35             |
|               | Av.        | 13.50            | 30.03            | 3.99             | 18.14            | 4.30             | 1.45             | 4.80             | 0.77             | 4.67             | 0.98             | 2.89             |

### FIGURE 3 Typical structural characteristic of weathered crust profile in the northwestern Junggar Basin (well P60 in Hongche area). 49,50

![Figure 3: Typical structural characteristic of weathered crust profile](image-url)
TABLE 2  Major element (%) analysis result of typical samples of Carboniferous volcanic rocks in the northwestern Junggar Basin

| Structure             | Weathered clay zone | Intensive weathered zoned | Weak weathered zone | Unweathered compacted zone |
|-----------------------|---------------------|--------------------------|---------------------|---------------------------|
| Samples               | ZG-1 | HC-1 | SN-1 | ZG-2 | HC-2 | SN-2 | ZG-3 | HC-3 | SN-3 | ZG-4 | HC-4 | SN-4 |
| SiO2                  | 50.535 | 58.986 | 55.225 | 54.679 | 56.378 | 58.142 | 57.398 | 63.452 | 60.357 | 69.859 | 64.424 |
| Na2O                  | 0.278  | 0.681  | 0.727  | 1.092  | 1.390  | 1.589  | 2.765  | 3.112  | 3.236  | 3.980  | 4.307  | 4.535  |
| MgO                   | 0.677  | 0.653  | 0.880  | 1.976  | 1.568  | 1.771  | 2.201  | 1.789  | 2.061  | 2.976  | 1.294  | 2.125  |
| Al2O3                 | 27.885 | 22.710 | 25.123 | 23.457 | 22.890 | 22.098 | 19.761 | 18.042 | 18.336 | 16.944 | 14.737 | 14.715 |
| P2O5                  | 0.567  | 0.678  | 0.790  | 0.445  | 0.542  | 0.688  | 0.212  | 0.150  | 0.207  | 0.137  | 0.094  | 0.198  |
| K2O                   | 0.412  | 0.976  | 0.567  | 0.559  | 2.725  | 1.025  | 0.890  | 3.157  | 1.460  | 0.682  | 4.307  | 1.512  |
| CaO                   | 0.227  | 0.123  | 0.541  | 1.105  | 0.779  | 1.625  | 1.876  | 1.002  | 4.798  | 2.471  | 1.331  | 5.144  |
| TiO2                  | 1.451  | 1.879  | 1.426  | 1.760  | 1.689  | 1.331  | 1.256  | 1.210  | 1.589  | 0.996  | 0.496  | 0.781  |
| MnO                   | 0.098  | 0.054  | 0.165  | 0.177  | 0.102  | 0.024  | 0.212  | 0.055  | 0.062  | 0.194  | 0.076  | 0.149  |
| Fe2O3                 | 17.109 | 12.577 | 13.994 | 14.626 | 10.341 | 10.643 | 11.762 | 6.865  | 7.215  | 9.087  | 4.043  | 5.569  |
| Total                 | 99.24  | 99.32  | 99.44  | 99.88  | 98.40  | 99.32  | 98.33  | 98.83  | 99.32  | 98.40  | 98.00  | 99.15  |
| Fi                    | 53.5   | 52.1   | 58.7   | 33.5   | 29.6   | 45.8   | 16.5   | 21.1   | 20.8   | 5.8    | 8.2    | 6.9    |

FIGURE 4  Reservoir pore types and characteristics. A, Almond stomata of basalt, 95 403, 399.28 m. B, Residue air pore, JL10, 3081.2 m. C, Intergranular pore, Che7, 1380 m. D, Shrink pore, G16, 2828.8 m. E, Dissolved intercrystal pore, J15, 766 m. F, Dissolved matrix pore, JL5, 3351.3 m. G, Intragranular dissolution of tuff, 403, 3898.7 m. H, Interparticle dissolution pores, 597, 2580.2 m. I, Mold pore, Che912, 1830 m.
of severe weathered fractures, developed solution cave, tectonic and weathered fractures, with great porosity and permeability, and is the main reservoir of the weathered profile. The weak weathered zone is characterized as a weak weathering level with low porosity and permeability. The unweathered compacted zone is composed of unweathered rock with poor porosity and permeability and is thought to be a nonreservoir zone. Therefore, the intensive weathered zone and part of the upper weak weathered zone are proposed as the most effective area to develop reservoirs.

### 4.3 Reservoir spatial type and properties

The volcanic reservoir spatial type is determined by tectonic background, Basin reconstruction, and petrology.\(^25,26\) The tectonic background of East China is that of an intracontinental rift with developed fault depression controlled by faults. The reservoir space is mainly from a native volcanic reservoir with limited weathering effects. The West Junggar Basin is classified as having an intracontinental island arc background subsequent to orogenic events.\(^27,28\) The volcanic rock experienced long-term exposure and leaching and intensive tectonic movements, which resulted in the main reservoir space of vuggy pores and fractures in addition to primary pores.

Primary pores include stomata pore (primary stomata pore and residue stomata pore), intercrystalline pore, and primary fracture.\(^29,30\) Primary stomata pores are the main reservoir space, develop in effusive basalt and andesite, have pore diameter of 0.5-3 mm, and account for 10%-15% of total pores. These pores are distributed independently or in clusters with poor connectivity (Figure 4A). The stomata pores filled by minerals in the late stages are called residue stomata pores (Figure 4B). Intercrystalline pores develop among phenocrysts with irregularly shaped pores <0.2 mm in diameter (Figure 4C). Shrink pores are generated from thermal expansion and contraction on volcanic glass or other components inside volcanic rock as the rock cools (Figure 4D).

Secondary pore includes dissolved phenocryst pore, dissolved matrix pore, dissolved intergranular pore, and mold pore. Dissolved intercrystal pores are formed through corrosion on intergranular pores and fine intergranular pores (Figure 4E). They are characterized as having irregular shapes with dissolution and harbor textures. The average diameters range from 0.1 to 0.6 mm, and the porosity is approximately 2%-8%. Dissolved phenocryst pores develop in basalt and andesite as the result of the dissolution of feldspar phenocrysts with cellular and cribiform textures. Dissolved matrix pores commonly occur in effusive andesite and basalt, which are

![Graphs showing FMI characteristics of volcanic rocks with different strike fractures.](image-url)
mainly composed of the glass matrix, and can be easily clayitized to form dissolved matrix pores as suitable volcanic reservoir space (Figure 4F). Dissolved intragranular pores are distributed in effusive andesite, erupting volcanic breccia and tuff with irregular shapes and harbor texture (Figure 4G). They are generated from corrosion on tuff, breccia, and crystal tuff after diagenesis. Interparticle dissolution pores form in andesite and volcanic breccia as a result of leaching on the matrix by atmospheric or freshwater. They are characterized as elongated or irregular in shape and have pore diameter of 0.15-0.5 mm (Figure 4H). Mold pores are distributed in volcanic breccia and are dominated by feldspar mold pores (Figure 4I). They are generated from the process through which corrosion occurs on the primary component, although the pore space shape is maintained.

Fractures form the effective reservoir space and significant seepage channel for volcanic weathered reservoirs.31 They are mainly divided into shrink fractures from lava cooling, weathered fractures, and tectonic fractures. According to the characteristics of sinusoidal curve, different types of fractures (horizontal fracture, low angle fracture, high angle fracture, and vertical fracture) can be identified from FMI imaging log. There is mainly high angle fracture and vertical fracture in the study area (Figure 5).32 Shrink fractures develop on lithologic interfaces and are generated from the shrinking of volcanic rocks during diagenesis, and the occurrence is thereby unstable (Figure 6A).33 Tectonic fractures mainly have characteristics of wide and high angle, smooth surface, stable occurrence, distant extension, and obvious direction, which are the results of multiple tectonic stress. They intersect each other to form fracture nets and play an important role in rock permeability (Figure 6B-D). Weathered fractures are also widely distributed, with low angle that develop near unconformity surface. They are thought to form from weathering and leaching and intersect with dissolved pores and tectonic fractures (Figure 6E,F).34,35 They cut the rock into pieces of varying sizes to display a network of irregular textures with disordered occurrences. In addition, they are usually filled or half-filled by carmine ferruginous or muddy materials, resulting in an insignificant contribution to the hydrocarbon reservoir (Figure 6B,C).

4.4 | Main factors of the development of weathered profile reservoirs

4.4.1 | Lithological characteristics of weathered profile reservoirs

Lithological characteristics (petrology), as the basis of the late evolution of reservoir spaces, determine mineral compositions, basic reservoir properties, and pore types of volcanic rocks.36 Under similar environments, different lithological characteristics offer different mechanical parameters, original physical properties, and dissolvable minerals, thereby resulting in significant differences in weathering and great effects on reservoir properties.

According to the statistics of more than 2000 physical property data (the data of Six-nine, Hongche, and Zhongguai areas are mainly collected) of main lithology in the study area (Figure 7), it shows that without weathering, only volcanic breccia is effective reservoir, and its average porosity is 8.6%. The erupting facies can form an effective reservoir with an average porosity of 8.2%. After weak weathered, volcanic breccia, andesite, and tuff can become effective reservoirs, with average porosities of 9.4%, 7.3%, and 6.5%, respectively. The eruption facies, volcanic facies, and effusive facies can all form effective reservoirs with average porosities of 9.7%, 8.6%, 7.8%, and 7.5%, respectively. After intensive weathered, granite is the least likely to form an effective reservoir, but it is still possible to form effective reservoir under the action of fracturing by the weathering.37 All other facies have different porosities. The average porosities of volcanic breccia, andesite, tuff, and basalt are 12.4%, 10.3%, 9.2%, and 7.6%, respectively. Except for the volcanic sedimentary facies, which cannot form effective reservoirs (the average porosity is 4.9%), all other facies can form effective reservoirs. It should be pointed out that porosity is the main basis for the formation of effective reservoirs in the study area, and the lower limit of effective porosity of proved petroleum reserves is 6.4%.13 The average porosities of the eruption facies, volcanic facies, effusive facies, and extrusive facies are 11.5%, 10.6%, 8.9%, and 6.8%, respectively. It is obvious that as the weathering level increases, the reservoir porosity increases, and weathering can significantly improve reservoir properties. In this area, both eruption volcanic breccia and effusive andesite are the best physical properties.

4.4.2 | Effect of leaching level on the thickness of weathered profile reservoirs

After the formation of volcanic rock, due to the long-term exposure on the ground, diagenesis and leaching can effectively improve reservoir physical properties by developing dissolved pores, caves, and fractures near the weathered profile. In general, longer exposure leads to higher leaching level, more developed dissolved products, and better reservoir properties, especially near the weathered profile (Figure 3).

According to the model relating weathered profile thickness and leaching duration proposed by Zou et al,4 we have

\[ d = alnt + b \] (3)

where d is the weathered profile thickness (m), t is the leaching duration (Ma), and a and b are parameters.
As the influence of the residual oceanic Basin, long-term sedimentation occurred in Permian with a maximum duration of 70 ± 15 Ma. According to the values of a and b in the northern Xinjiang, the maximum thickness of Carboniferous volcanic weathered profile is 380 m in the study area. Based on more than 2000 porosity samples from 40 drilling wells in Six-nine area, Zhongguai area, and Hongche area, the correlation with the distance to the top of the weathered profile suggests that the samples with porosities exceeding 15% are mainly located within 400 m of the weathered layer, and the samples with porosities ranging from 6% to 15% are mainly distributed 400-600 m below the weathered layer. With increasing distance from the top Carboniferous, the porosity is significantly reduced, consistent with Equation 3 (Figure 8). However, due to the influence of fractures, there are many abnormal points, which also proves that fractures can effectively improve the reservoir performance. Meanwhile, the faults (fractures) cause surface water to permeate and dissolve reservoirs, leading to advanced leaching and great extension of weathered profile thickness. For example, in Hongche area and in some wells near the main fault on the hanging side of the Ke-Bai fault (Ke 82, Gu 133, 7518, Gu 29 and 801), effective reservoirs can form even 1000 m from the top of the weathered profile.

Taking Zhongguai area as an example, according to the well-logging identification of weathered profile structure and reservoir physical properties, combined with Equation 3, the plane distribution of weathered profile of Carboniferous volcanic rock is analyzed (Figure 9). The weathered profile in Zhongguai area is widely developed, which indicates that it has been intensively weathered and leached. The thickness of the intensive weathered zone is 120-200m, and the thickness is gradually reduced from west to east, indicating that the weathered degree is gradually weakened. The area with large weathered thickness is mainly distributed in the area of wells 573-575 in the northern Five-eight area, and wells 597-596, K021-H56A, and JL10-H019 in the central area.

### 4.4.3 Improvement in weathered profile reservoir permeability through tectonic movements

Tectonic movements can affect volcanic weathered reservoirs in two aspects. First, weathering and leaching from paleo-uplift and slope areas formed during tectonic
movements can significantly improve the physical properties of volcanic rock. Carboniferous-Early Permian magmatic activities provided basic conditions for the formation and distribution of volcanic reservoirs. Hercynian tectonic movements occurring in the Mid-Late Permian caused the northwest Junggar area to be exposed to the surface environment. Long-term weathering and leaching widely grew weathered profile on the tops of different lithological phases. The volcanic rock located on the paleo-uplift and slope can easily develop secondary pores. In contrast, the volcanic rocks in the lower area experienced weak weathering and leaching, resulting in poor permeability. Therefore, the hydrocarbons formed in the northwest Junggar area are all distributed on the paleo-uplifts or slopes.

Second, tectonic movements produce a plentiful number of fractures in the compacted volcanic rock, which is the key to improve reservoir permeability. Multistage episodic tectonic movements, including the Hercynian, Indosinian, Yanshanian, and Himalayan, have affected the development and distribution of faults and fractures in different levels. Under the tectonic stress, rock strata are lifted and reformed, and fractures and faults are produced. In addition, faults control the development of fractures, that is, higher levels of faulting can control wider distribution of fractures. The development of fractures can expand reservoir space and connect isolated air pores. In addition, they also become important passages for groundwater and organic acid and play a significant role in dissolution. Therefore, they are the main factor in the generation of secondary dissolved pores and improving seepage performance. According to the fracture densities of the cores at different distances from the fault, fracture density is inversely correlated with distance from the fault. The high-density area is mainly located within 600 m of the main fault. The level of development of fractures increases with increasing distance. Moreover, in the area at distances exceeding 600 m, fracture density is reduced, and the development level is also decreased (Figure 10).

Fractures can cause the changes of amplitude, frequency, phase, and other attributes of seismic reflection. Therefore, according to the seismic attributes detected by seismic data, fracture development zones can be predicted, and the coherence and curvature attributes are mature and effective methods for fracture prediction at present. By extracting seismic coherence and curvature attributes in Zhongguai area (Figure 11), and combining the fracture prediction results of different attributes, the seismic fracture prediction results in the study area are obtained (Figure 12). Generally speaking, the fracture development area is mainly located in the area of wells 563-591-575-590-573, wells 593-572-568-596, and wells 574-561-k75-k77 in the Five-eight area; wells K021-H56a, wells H019-G150-G148-Jl10-Ji11-Jl6, well JL7, west of well 598, and well G10 in the central area; wells K77-K010-JL4-K79-K301 in the east slope of Zhongguai area, and the south of well JL2.
The development and distribution of primary pores are controlled by the process of magma ejecting from the surface, intruding into the ground, and forming rocks by condensation and consolidation, and after the formation of volcanic rocks, secondary pore space is formed due to the influence of the environment. This process is collectively referred to as the diagenetic stage of volcanic rocks. The diagenesis in the study area can be divided into constructive diagenesis and destructive diagenesis. Constructive diagenesis plays an important role in improving reservoir porosity and permeability.

Constructive diagenesis mainly includes condensation and contraction, volatilization and dispersion, weathering and leaching, tectonic fragmentation and dissolution. Condensation and shrinkage refers to the volume shrinkage caused by the rapid cooling of hot molten magma after it erupts to the surface, forming round and arc-shaped shrinkage pores and fractures, but they are small in size and high in filling degree, and have little contribution to the reservoir (Figure 13A).
In the near surface or shallow environment, the magma condenses and shrinks, and the water, carbon dioxide, chlorine, fluorine, and other volatile components in the magma escape to form pores and micropores (Figure 13B,C), which is the most important diagenesis for the formation of primary pores. The formation of volcanic reservoir by weathering and leaching is mainly divided into two aspects. First, a large number of weathered fractures are formed to provide a channel for acid liquid to enter into volcanic rock mass, thus forming a large number of secondary pores (Figure 4F,H). Second, the weathered clay can effectively inhibit petroleum escape and secondary migration. After the formation of volcanic rocks, they suffered from multistage tectonic stress and formed multistage tectonic fractures, which interlaced with each other and formed a reservoir space of tectonic fractures-dissolution pores (Figure 13D,E). Dissolution mainly occurs in the burial diagenetic stage. Organic acids, inorganic acids, and other soluble substances formed in the deep crust or in the process of hydrocarbon expulsion enter the volcanic rocks along the unconformity and fracture, and then dissolve calcite, plagioclase, zeolite, and other soluble components, resulting in a large number of dissolution pores and caves (Figure 13F).

In addition, there are many destructive diagenesis in the study area, including compaction, filling, and fusion.
Compaction refers to the reduction of primary pores under the pressure of overlying sediments after the formation of volcanic rocks. After the volcanic eruption solidified, the pores or fractures will be filled with various secondary minerals, forming the residual stomatal structure, almond structure, and other filling structures (Figure 13G,H). However, the early filling materials such as zeolite and calcite can provide material basis for the later dissolution. Under the influence of the overlying formation pressure, the pyroclastic materials are flattened to different degrees and arranged directionally (Figure 13I), mainly occurring in the pyroclastic rocks, which is the main reason for the reduction of primary pores.

Since the Permian, volcanic rocks were slowly buried in the shallow ground. During that process, the volcanic rocks were compacted and filled to different levels. The pore space produced during weathering and leaching was compressed or partially refilled, and the capability of reservoir was thereby reduced. At the same time, new tectonic fractures were continuously produced to provide new passages and reservoir space for reservoir improvement. With increasing burial depth, the volcanic rocks entered the deep-burying stage. The depressed area near the volcanic rock bodies had already generated mature hydrocarbon rocks. Organic matter was decomposed into monocarboxylic and dicarboxylic acids through decarboxylation and released carbon dioxide and nitrides into the compacted water and interlayer water from diagenesis of mud rock. This process can dissolve major minerals such as aluminosilicate and mafic silicate and filling minerals such as clays and carbonates to further improve the reservoir space properties.

5 | DISCUSSION

5.1 | Development of the volcanic rock weathered profile reservoir

The formation of volcanic rock weathered profile reservoirs is highly associated with the type of geological processes, change in reservoir space, and their interactions. The analysis of the tectonic background, weathered profile structure, reservoir properties, and main controlling factors suggest
that the formation of the weathered volcanic reservoir results from the evolution of a series of processes that include the formation, development, and reformation of pores and fractures. On the whole, the development and distribution of the weathered volcanic reservoir in the study area is affected by multiple factors such as lithology, petrology, tectonic movement, fractures, and pores, which generate the reservoir characteristics of complicated superimposition, poor connection, and small distribution area and result in large differences in permeability and great variations in well production. Based on recent studies of regional geology, geochemistry, and geophysics (magnetism and gravitation), since the Phanerozoic, the regional tectonics of the Junggar Basin experienced a formation and cleavage period, an opening and closing paleo-craton period, and a new craton intraplate thrust period. The volcanic rocks were strongly lifted, folded, and corroded in the Carboniferous-Permian after their formation. The reservoir properties are improved by the unconformable surfaces on the top of Carboniferous formed through weathering, leaching, and internal secondary fractures, in which the main faults controlled by the Kebai fault belt and Hongche fault belt provide passages for hydrocarbon transportation. Hydrocarbons are deposited in step and block form following the main controlling fault. In addition, above the Carboniferous deposits, the upper Wuerhe Formation lacustrine mud rock forms an effective reservoir-seal combination with the lower Carboniferous and generates multiple volcanic weathering hydrocarbon reservoirs with different scales.43,44

Due to the thrusting structure influence, the development situations and hanging wall and footwall modes are different. With the effect of thrusting, the hanging wall of the Kebai fault belt develops a plentiful number of faults in step form, resulting in the step distribution of hydrocarbon reservoirs. After the formation of a hydrocarbon reservoir,
some deposits are transported to the hanging wall to form a primary step hydrocarbon reservoir and then through transport of faults and unconformable planes generate a secondary step hydrocarbon reservoir, it is accumulation mechanism and model of a volcanic rock reservoir with a unconformity adjacent to source rock. The thrust belt front was elevated and weathered for a long time. The volcanic weathered profile that formed as the result of faulting processes had a great thickness, and there is a significant positive correlation between the weathered thickness and reservoir thickness (Figure 14A). In Zhongguai area, after volcanic rock formed in Carboniferous period, there were strong uplift, fold, and denudation. Unconformity formed by weathering-leaching and its secondary faults improved the reservoir performance. Lacustrine mudstone of upper Wuerhe Formation and Carboniferous Formation formed favorable reservoir-seal assemblage. Main faults provided paths for oil and gas migration, and formed banded and block-like hydrocarbon accumulation zone along both sides of the main faults. Thus, it formed different scales of volcanic weathered crust reservoirs (Figure 14B).

5.2 Distribution of volcanic rock weathered profile deposits

The formation of the weathered volcanic reservoir has been controlled by multiple factors, with effects due to hydrocarbon source, lithology (petrology), fault, paleo-structure (paleo-uplift), weathering and leaching on unconformable faces, and cap rock. Therefore, oil and gas is distributed following three areas (near the fault belt, structural elevated zone, and the favorable lithofacies zone).

The hydrocarbon distribution is vertically controlled by Carboniferous unconformable planes. Those at shorter distances from unconformable planes display a higher level of weathering and leaching on the volcanic rocks and better reservoir capability. With increasing distance, porosity and permeability are both significantly reduced (Figure 15). The statistical analyses on hydrocarbon segments in the study area suggest that most of the hydrocarbons are located within 20-240 m from the top Carboniferous unconformable plane, in which the hydrocarbons are concentrated at depths of 20-200 m. This indicates that vertically, the hydrocarbons are...
concentrated within a certain depth below the unconformable face and that the aggregation degree rises near the unconformable face.

The hydrocarbon distribution is associated with fault belts, unconformable faces (paleogeomorphology), and petrology distribution on the plane. Under the stress environment, the entire stratum is lifted for weathering and leaching from the surface environment. Intensive corrosion and leaching occur on the elevated and slope areas of paleogeomorphology, especially on the material of almond-like inclusion. Precipitation water infiltrates along faults, and therefore, the faults and fine fractures can be easily dissolved. The lower area is covered by weathered material for further sedimentation. The weak dissolution weathering results in a thin weathered profile. Thus, volcanic rock weathered profile reservoirs are mainly distributed on the paleogeomorphological elevated area, slope, and mature faults, especially mature faults that can easily generate high-quality reservoirs.

6 CONCLUSIONS

The Carboniferous volcanic rock in the northwest Junggar Basin is dominated by magmatic rock, volcanic breccia, and breccia magmatic rock, which is an intraplate island arc environment. From top to bottom, the weathered profile can be divided into weathered clay zone, intensive weathered zone, weak weathered zone, and compacted unweathered zone, in which both the intensive weathered zone and part of weak weathered zone can be the most effective area for high-quality reservoirs.

Volcanic rock weathered profile reservoir spaces mainly include primary pores, secondary pores, and fractures. The main factors that determine weathered profile reservoirs are lithology (lithofacies), weathering and leaching, fault (fracture), and diagenesis. The lithology (lithofacies) controls the reservoir physical properties, weathering and leaching control reservoir thickness, fault (fractures) controls reservoir capability and quality, and constructive diagenesis plays an important role in improving reservoir porosity and permeability.

The distribution of weathered profile reservoirs is determined. On the plane, the hydrocarbons are mainly distributed near the fault belt, the structural elevated zone, and the favorable lithofacies zone. On the vertical profile, they are all located within a certain depth near the top of the weathered profile, and the best range is 20-200 m. This study provides significant scientific guidance on the exploration of volcanic rock weathered deposits and provides new ideas and a geological basis for future hydrocarbon exploration and exploitation.

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CONFLICT OF INTEREST

The author(s) declared no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

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