

Research Article

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Influence of nappe structure on the Carboniferous volcanic reservoir in the middle of the Hongche Fault Zone, Junggar Basin, China

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Abstract: This work presents an in-depth examination of the Carboniferous volcanic reservoir within the CH471 well area, situated in the central portion of the Hongche fault zone on the northwestern margin of the Junggar Basin. Leveraging seismic data and well connection comparisons, we scrutinize the tectonic evolution model and elucidate the impact of the nappe structure of the Hongche fault zone on the volcanic reservoir. The study has obtained the following understanding: after the formation of Carboniferous volcanic rocks, affected by the Hongche fault structure, a series of structural superpositions from extension to extrusion and finally thrust occurred, resulting in a northwestward tilt of the volcanic rock mass, and a large number of cracks were generated inside the rock mass. At the same time, the top was uplifted and affected by weathering and leaching to form a weathering crust, eventually forming a reservoir. The northern part is located in the edge area of the eruption center, and the rock mass has good stratification. The rock strata have certain constraints on the reservoir distribution, and the reservoir is inclined along the rock mass. The southern part is close to the eruption center and features large volcanic breccia accumulation bodies with strong internal heterogeneity. The reservoir developed mainly in the superposition of the range of control of the weathering crust and dense fracture development, and the rock mass

morphology does not control the area. Structure is the key to forming a volcanic rock reservoir, mainly reflected in the following aspects. First, tectonic activity is accompanied by fracture development, and fractures are densely developed in areas with strong activity, which can effectively improve the physical properties of volcanic reservoirs. Second, tectonic activity leads to the strata uplift and weathering denudation, forming a weathering crust. Within the range of control of weathering and leaching, the physical properties of volcanic rocks are improved, and it is easier to form high-quality reservoirs. Third, the distribution of volcanic rock masses is controlled by tectonic activity, which affects the reservoir controlled by the dominant lithology.

Keywords: Hongche fault zone, tectonic evolution, Carboniferous, volcanic reservoir, connected well comparison, seismic cross-section

1 Introduction

Volcanic oil reservoirs were first discovered in the eighteenth century [1]. It has achieved certain results in many countries and regions around the world. For example, the Niigata Basin in Japan, the North Cuba Basin in Cuba, and the Neuquen Basin in Argentina have obtained industrial oil flows and large-scale reserves [2–7]. The discovery of volcanic oil and gas reservoirs in China began in the 1950s, and industrial oil flows were first encountered in Carboniferous volcanic rocks in the Junggar Basin [8]. Later, breakthroughs were made in 14 petroliferous basins, such as Santanghu Basin and Songliao Basin [9,10]. By comparing the volcanic oil and gas reservoirs found in the world, we can see that almost all types of volcanic rocks have the precedent of forming effective reservoirs, from acidic volcanic rocks to basic volcanic rocks, and whether the lithofacies is explosive, overflow, or sedimentary facies of volcanic rocks [11,12]. This phenomenon is due to the fact that most of the primary pores and fractures of volcanic rocks are isolated from each other and lack connectivity, it

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is difficult to form high-quality reservoirs in volcanic rocks. The formation of most volcanic reservoirs depends on later transformation and is controlled by weathering, leaching, tectonic evolution, and diagenesis [13–15]. Therefore, the formation conditions of volcanic reservoirs are more random than those of conventional reservoirs.

Reservoirs have always been the focus of exploration and development of volcanic oil and gas reservoirs [16–18]. Early studies on volcanic reservoirs mainly focused on lithofacies, but the final results were not ideal due to the particularity of the volcanic reservoir mentioned above [19]. The study of volcanic rock reservoirs has gradually turned to fracture and weathering leaching and has achieved good results [20–27]. However, research on the influence of tectonic evolution on volcanic reservoirs is still relatively weak, especially against a thrust-nappe tectonic background [28,29].

This study takes the Carboniferous volcanic oil and gas reservoirs in the CH471 well area under the complex tectonic background of the hanging wall of the Hongche fault

zone in the northwestern margin of the Junggar Basin as an example. Based on previous studies, through a combination of wells and earthquakes, the influence of the thrust nappe structure on the distribution of volcanic reservoirs is discussed, and the transformation of volcanic reservoirs in different tectonic stages is discussed. This study provides a theoretical reference for exploring volcanic reservoirs in this region and similar regional backgrounds.

2 Geological setting

The Junggar Basin is located at the junction of Kazakhstan, Siberia, and the Tarim plates. It was formed during the collision and closure of the Central Asian Orogenic Belt (CAOB) in the late Paleozoic and is one of its main tectonic units (Figure 1a) [30]. The Junggar Basin is a triangle bounded by the Junggar fold mountain system in the

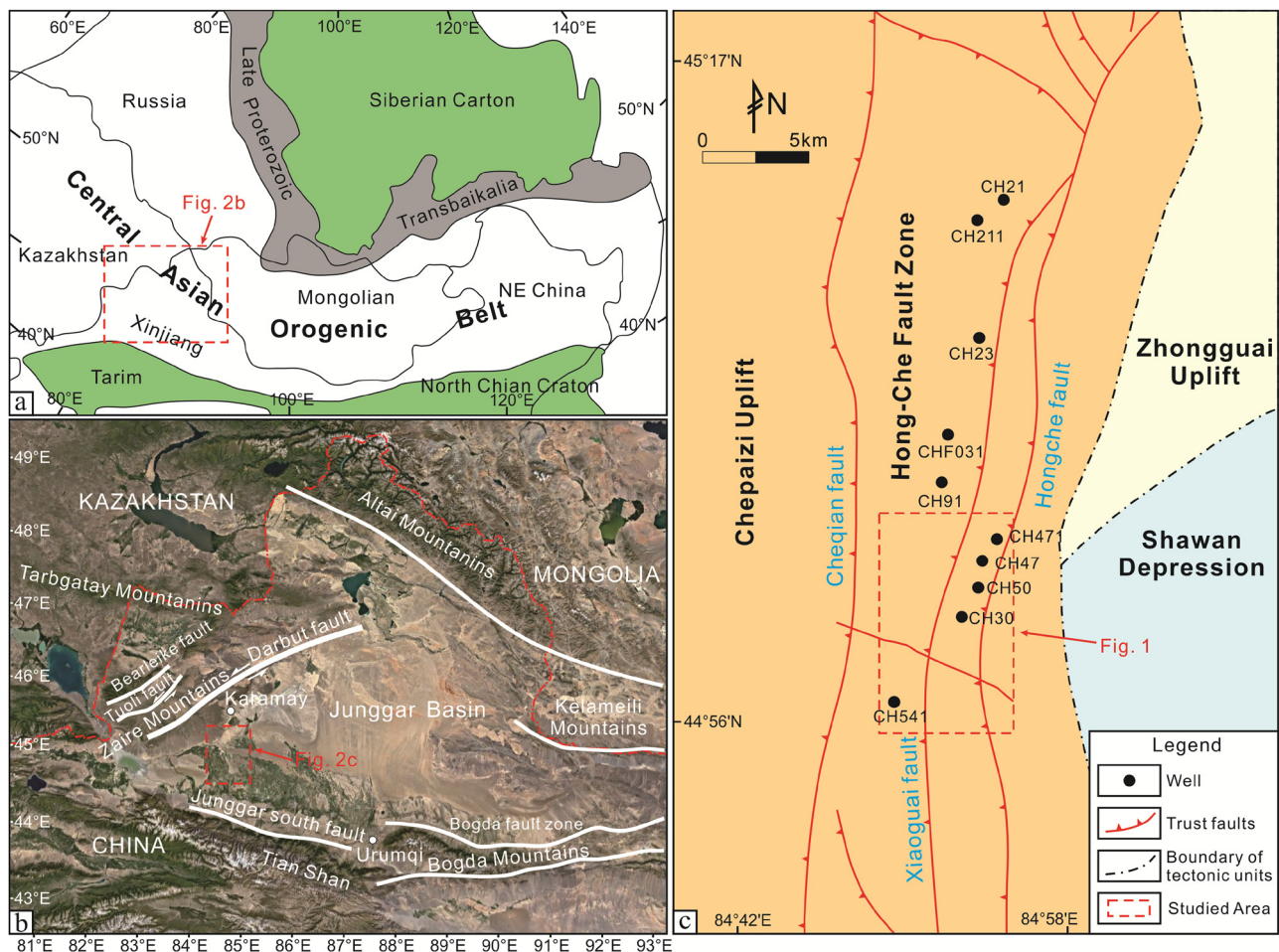


Figure 1: Location and geological background of the study area. (a) The tectonic position of Junggar Basin in the CAOB; (b) main tectonic units and faults around Junggar Basin; and (c) adjacent tectonic units and faults of Hongche fault zone.

northwest, the Altai orogenic belt in the northeast, and the Tianshan Mountains in the south (Figure 1b) [31].

The Hongche fault zone is located at the junction of the northwestern margin of the Junggar Basin and the Western Junggar fold mountain system (Figure 1c). It is a large-scale fault zone formed by a combination of thrust or overthrust faults of different periods and scales [32–34]. The overall distribution is NE-trending, with a total length of 80 km and a width of approximately 10–20 km. The western part is the Chepaizi uplift, and the eastern part is the Shawan sag, with an area of approximately 1,500 km². The activity of the West Junggar orogenic belt influences its formation and evolution. There is some controversy about the formation time of the Hongche fault, but most studies suggest that its activity began in the late Carboniferous [35–39]. The formation of the Hongche fault zone is divided into five tectonic stages: (1) in the late Carboniferous–early Permian post-orogenic extensional background, the fault began to form; (2) the tension in the middle–late Permian turned into extrusion, and thrusting began; (3) in the Early Triassic, the tension was inherited and superimposed based on the thrust nappe structure; (4) the Jurassic–Cretaceous activity began to weaken, and oscillation and fluctuation gradually began; and (5) during the Cenozoic, thick Neogene strata were deposited in the Chepaizi area, and no strong deformation was found.

The study area is located in the Carboniferous volcanic reservoir of the CH471 well area in the middle section of the hanging wall of the Hongche fault zone. The discovery of this reservoir began with the deployment of the CH47 well in 1985, which was tested in the Carboniferous volcanic rock section and obtained industrial oil flow. More than 60 million tons of proven petroleum geological reserves have been found in the Carboniferous volcanic reservoir, which has an oil-bearing area of 34.64 km².

After the formation of Carboniferous volcanic rocks, the study area has undergone superimposed transformation of multi-stage tectonic movements, such as the Hercynian, Indosinian, Yanshan, and Himalayan movements, and its internal structure is complex [31,40–44]. Laterally, two groups of reverse faults are present in the north-south and east-west directions (Figure 2). Among them, the north-south fault dominated by the Hongche fault has the largest scale, many cutting horizons, and an early formation time. The other group of east-west faults has a small fault distance, the main fault layer is Carboniferous in age, the formation time is late, and the north-south faults formed early are cut. Vertically, Carboniferous, Permian, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary strata are present from bottom to top. The Carboniferous strata are the main research object. The top boundary of the strata is characterized by high

values in the southwest and low values in the northeast, and the whole set of strata is a monocline in the northeast direction. It unconformably overlies the overlying Permian Lower Wuerhe Formation (P_2w), resulting in the lack of the Jiamuhe Formation (P_2j), Fengcheng Formation (P_2f), and Xiazijie Formation (P_2x). In addition, the Carboniferous strata are dominated by igneous rocks, including tuff, basalt, andesite, and volcanic breccia.

3 Data and study methods

The average thickness of Carboniferous volcanic rocks in the study area is more than 600 m. However, the drilling depth of the collected drilling data in this area is relatively shallow. The main drilling interval is located in the middle and upper part of the Carboniferous system, and the drilling fails to penetrate the Carboniferous strata. In addition, volcanic rocks have the characteristics of strong heterogeneity and rapid lithological changes, which makes it difficult to identify and explain the distribution and morphology of volcanic rock masses by single-well lithology combined with well comparison. However, due to the good quality of seismic data in the study area, the seismic reflection waves of the explosive phase are chaotic, and the seismic waves of the overflow phase are well-layered. Therefore, we use seismic and logging data to study the Carboniferous volcanic rocks [45–47].

The seismic data used in this study came from 3D seismic data collected in the CH45 well area in 2017. The vertical axis of the seismic data has now been converted to elevation, which is currently in meters. The stratigraphic calibration and fault identification of seismic data are mainly based on research by the Xinjiang Oilfield Company. There were 15 individual well logs, including 11 appraisal Wells and 4 development Wells. Three seismic profiles and corresponding well profiles are drawn, of which two E-W profiles are located in the north and south of the study area, and the other N-S profile runs through the whole study area. The longitudinal distribution characteristics of the volcanic rock mass are analyzed from the north-south and east-west directions, and its structural form is clarified (Figure 2).

4 Results

4.1 Structural form of north-south volcanic rocks

The study area's north-south seismic profile shows (Figure 3) that the volcanic rock mass has not undergone large-scale

deformation in the north–south direction, and the overall thickness changed little, manifested as the morphological characteristics of the original volcanic accumulation body. The seismic interpretation results show several east-west reverse faults with small fault distances, and the main fault layer is Carboniferous age. The seismic reflection of the southern section is relatively messy and should be near the eruption center, mainly in the explosive phase, and the stratification is poor. The seismic reflections of the northern section have clear layered characteristics and relatively good continuity. The seismic reflections are part of the draped body, which is composed of various lithological

interbeds, such as explosive facies, overflow facies, and volcanic sedimentary facies.

4.2 Structural form of east-west volcanic rocks (northern section)

The Carboniferous volcanic rocks in the northern part of the study area have the characteristics of layered seismic reflection and good continuity (Figure 4). The seismic interpretation results show that the north-south fault is a thrust

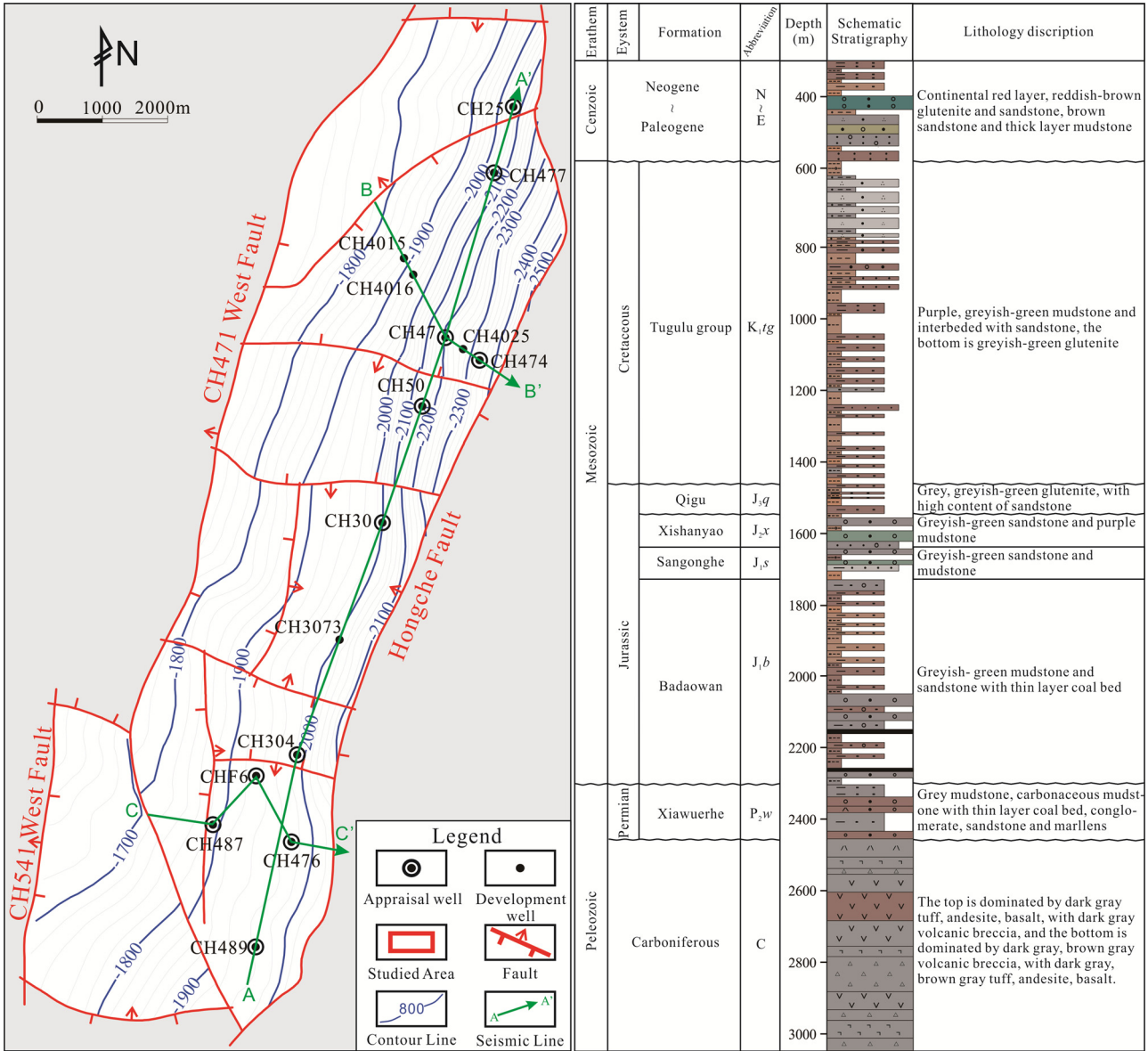


Figure 2: Regional structural map and stratigraphic histogram of the study area.

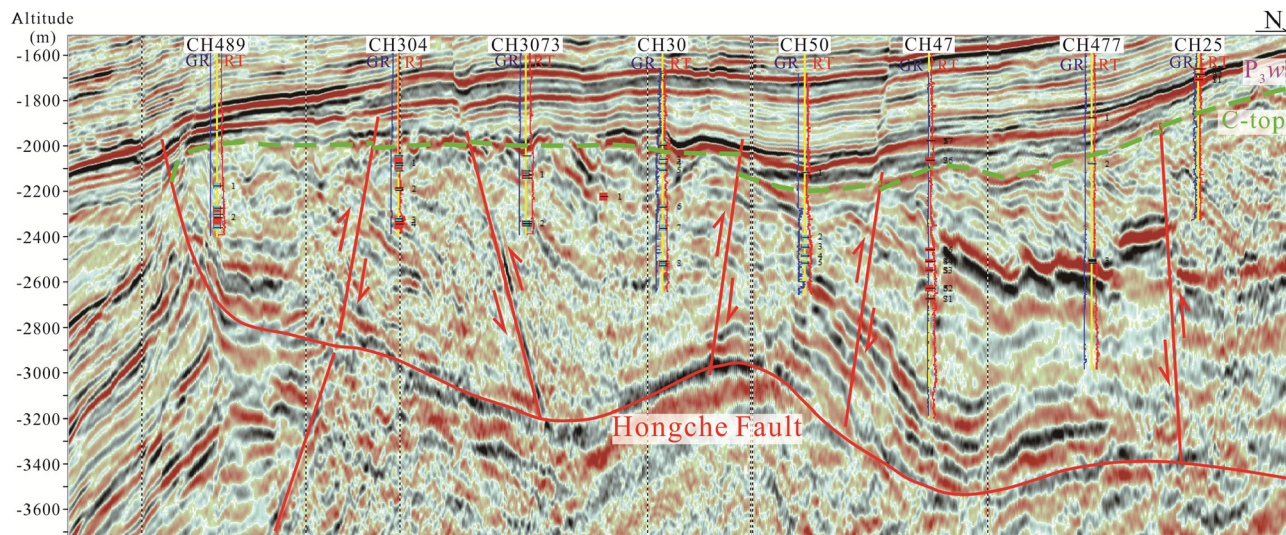


Figure 3: Through CH489-CH25 well seismic profile (A-A').

fault dominated by the Hongche fault zone, with a large fracture distance and a lot of stratum cutting. Combined with the analysis of the north-south section, the rock mass tends toward the northwest, with dip angles of 20–50°, oblique to the overlying strata, and gradually pinches out from west to east. The analysis shows that this feature is due to the influence of the Hongche fault's thrust nappe after the volcanic rock's formation, which leads to the deformation and inclination of the volcanic rock mass. The rock mass is uplifted and deposited again after weathering and denudation. The top is the ancient weathering

crust residue, not the strata, characterized by an oblique intersection with the overlying strata.

4.3 Structural form of east-west volcanic rocks (southern section)

Due to the proximity to the eruption center, extremely thick volcanic breccia accumulations are present in the southern part of the study area, and seismic reflections

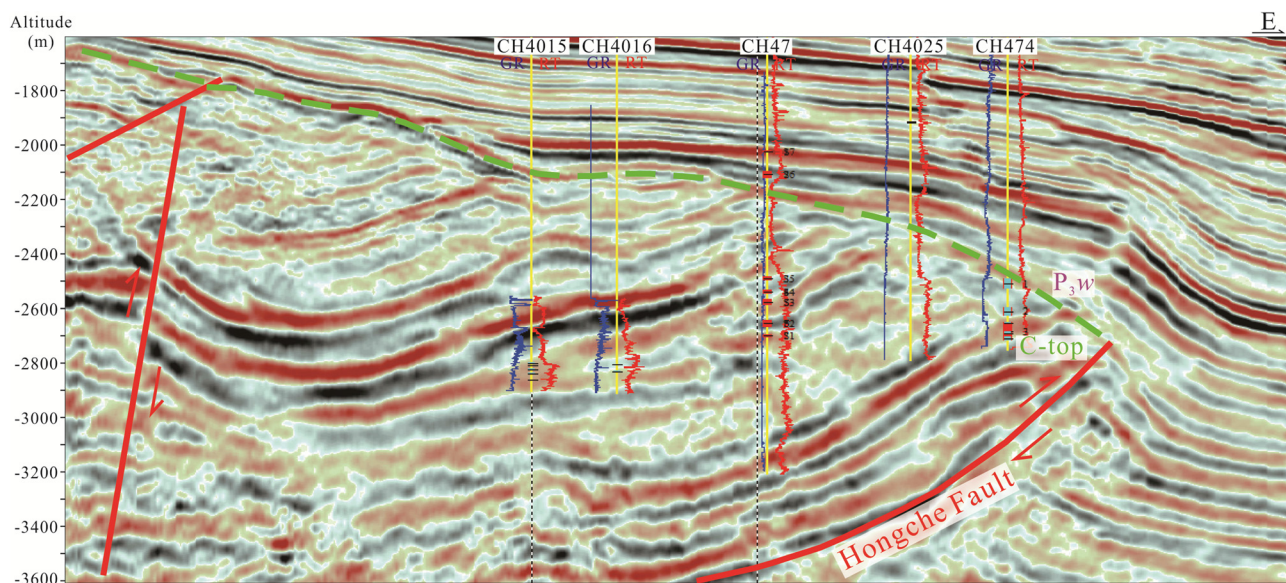


Figure 4: Through CH4015-CH474 well seismic profile (B-B').

are more disorderly and do not have stratification. It is difficult to ascertain whether the volcanic rock mass is inclined from the seismic profile and whether the top has been weathered and eroded (Figure 5). However, some draped bodies are still in the section's western part, which is stratified, indicating that the volcanic rock mass is inclined in a northwest direction.

5 Discussion

5.1 Evolutionary model of Carboniferous volcanic rocks

Based on the above research, combined with the comparative analysis of different tectonic evolution stages of the Hongche fault, the evolution model of the Carboniferous volcanic rock mass in the study area is established, and it is mainly divided into the following four stages:

(1) In the first stage, the early Carboniferous volcanic rocks erupted and accumulated to form the original volcanic edifice (Figure 6a). The lower part developed thick explosive breccia around the eruption center and gradually thinned toward both sides. The upper part developed a draped shape composed of overflow facies, explosive facies, and volcanic sedimentary layers.

(2) In the second stage, from the late Carboniferous to the end of the Permian, the volcanic rock mass experienced

a series of complex structural superpositions. From the late Carboniferous to the early Permian, a fault began to form under the tensile background of the closure of the ocean basin until the post-orogenic extension. At the end of the early Permian, the stress field reversed, the reverse fault developed, and the hanging wall of the fault was uplifted (Figure 6b). In the middle-late Permian, the extrusion pressure increased, and the thrust nappe began. The volcanic rock mass was deformed by extrusion and inclined to the northwest.

(3) The third stage was synchronous with the second stage. Affected by the uplift and denudation of the hanging wall of the thrust fault, the top of the inclined volcanic rock mass is denuded, and some Permian strata are missing (Figure 6c). As a result, the Carboniferous strata and the overlying strata of the Permian Lower Urho Formation (P_2w) obliquely intersect and are in unconformable contact.

(4) In the fourth stage, the Triassic strata inherited the structural form of the late Permian strata and were further compressed, but the structural strength weakened. Based on the previous deformation, the high-angle thrust was superimposed. The Triassic strata in the whole structural area were cut off at a high angle, resulting in a lack of Triassic strata in the study area. The subsequent Jurassic–Cretaceous tectonics further weakened, the formation thickness was stable, faults and folds were rarely developed, and minor unconformities appeared in some areas. During the Cenozoic, thick Neogene strata were deposited and finally formed their present shape (Figure 6d).

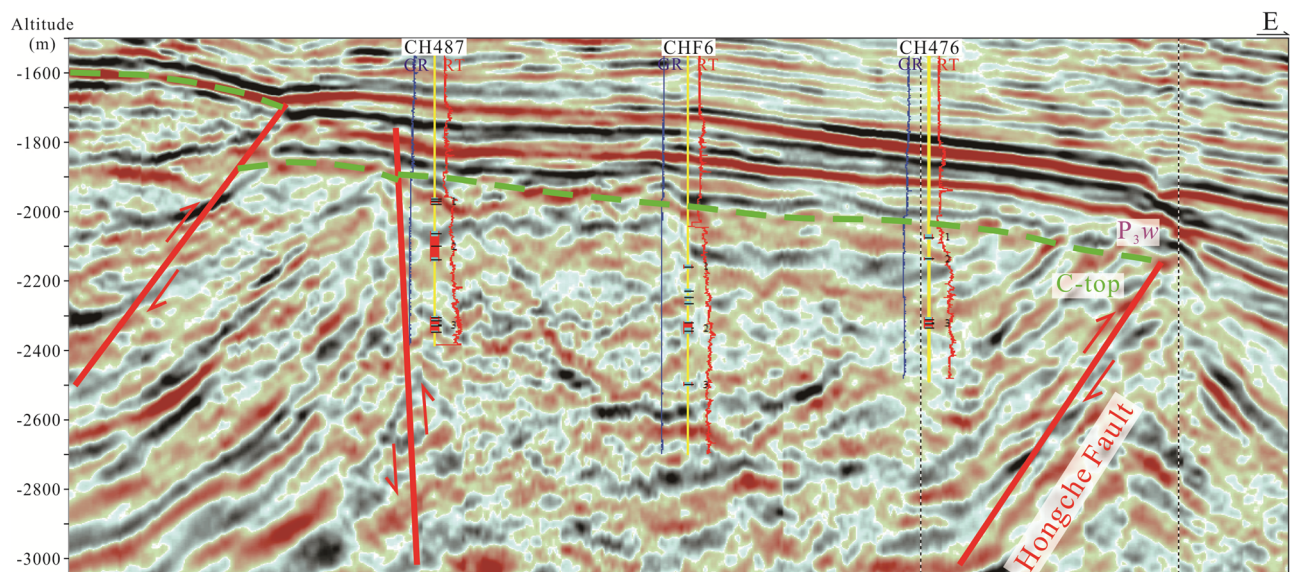


Figure 5: Through CH487-CH476 well seismic profile (C-C').

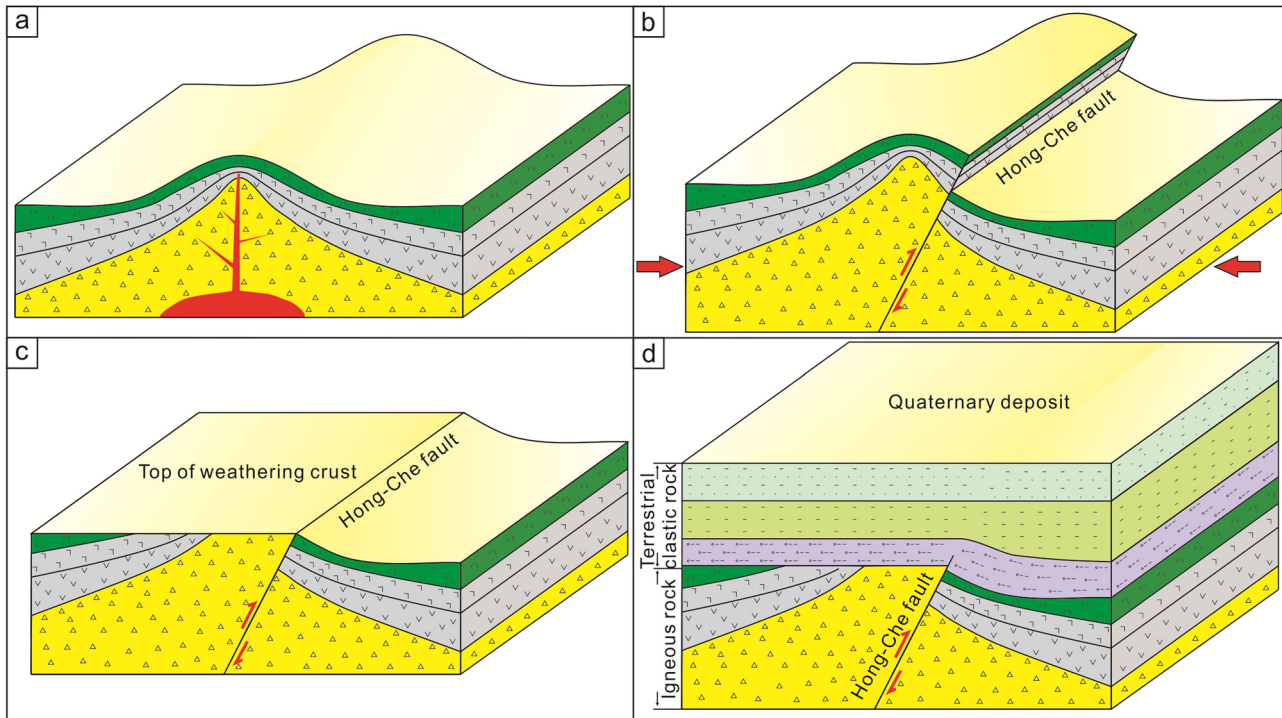


Figure 6: Evolution pattern of Carboniferous volcanic rock mass in the study area. (a) Primitive volcanic apparatus; (b) uplift of thrust nappe strata; (c) the top is eroded by weathering; and (d) present stage.

5.2 Comparative analysis of the vertical distribution of volcanic reservoirs

Based on clarifying the tectonic evolution of the Carboniferous volcanic rock mass, the vertical distribution pattern map of the reservoir in the study area is drawn, and the comparison of the well-connected oil layers verifies the distribution pattern of the reservoir. This study compares the east-west section and the north-south section of the study area and discusses the differences between the southern and northern parts of the study area.

5.2.1 Comparative analysis of the north-south reservoir

The vertical distribution of the north-south volcanic reservoir shows that (Figure 7) there is no large deformation in the north-south direction of the volcanic rock mass. The southern section is close to the eruption center, and a thick volcanic breccia accumulation body is developed. The lithology is singular and does not have stratification. Due to the strong internal heterogeneity of the volcanic breccia accumulation body, reservoir development is less constrained by lithology and is more affected by fault (fracture) development and weathering crust control [48–52]. The reservoir is mainly developed and distributed within the range of control of the top weathering crust. The

northern section is located at the edge of the eruption center and is mainly composed of volcanic breccia, andesite, and tuff. It has the characteristics of good stratification, rapid lithological change, and strong heterogeneity, and the distribution of the rock mass has a certain regularity. Lithological changes have a certain degree of constraint on the reservoir, and they control the development of the reservoir along the dominant lithology.

The comparison of the north-south wells (Figure 8) shows that the volcanic oil layers in the southern section are mainly distributed in the range of control of the weathering crust within 400 m from the top boundary of the Carboniferous system and are constrained by the fault distribution to a certain extent. In addition to the influence of the weathering crust and fault (fracture) control, the volcanic oil layer in the northern section is also affected by the distribution of the rock mass, and the oil layer is inclined along the rock mass. The above characteristics are consistent with the reservoir distribution model.

5.2.2 Comparative analysis of east-west reservoirs (northern part of the study area)

The map showing the longitudinal distribution of the east-west volcanic reservoir in the northern part of the study

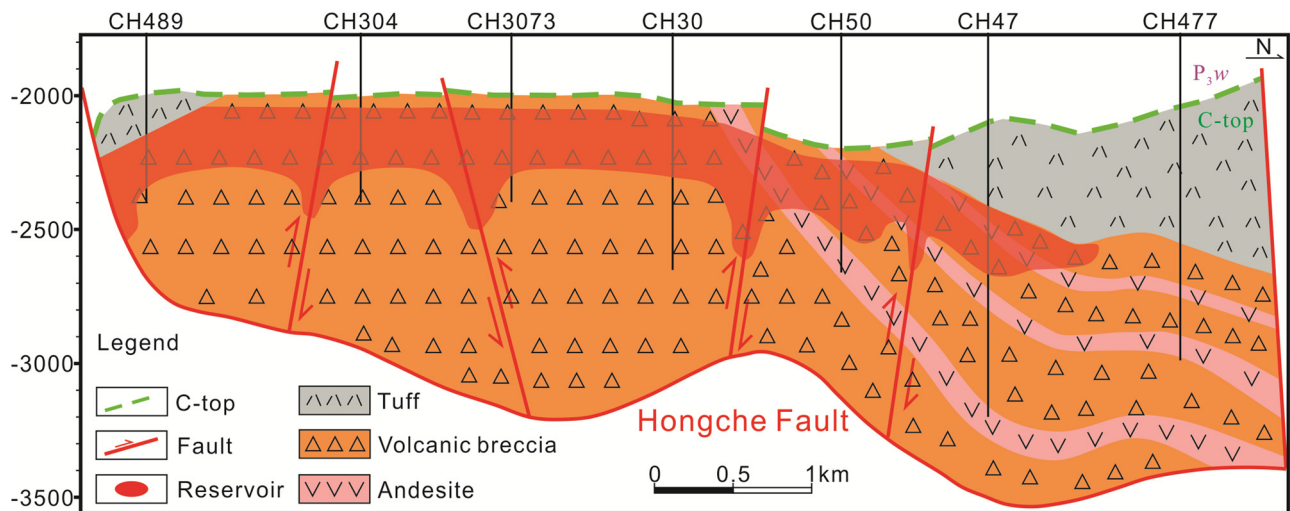


Figure 7: The distribution pattern of CH489-CH477 reservoir (A-A').

area shows that the volcanic rock strata in the northern section tilt from east to west (20–50°) and rapidly pinch out from west to east, and the distribution of the rock mass shows certain regularity (Figure 9). Although the volcanic rock mass has strong heterogeneity and the physical properties of different parts are different due to the influence of fracture development and weathering, the difference in the rock mass strength and wind resistance of different lithologies is greater. Under the premise of strong stratification and regularity of the volcanic rock mass, the lithology has

certain constraints on the reservoir distribution; thus, the reservoir is affected by the inclination of the volcanic rock mass and distributed along the inclination direction of the rock mass, with certain extensibility.

The comparison of east-west wells in the northern part of the study area shows that (Figure 10) the distribution of oil layers is affected by the inclination of the rock mass, and the oil layers are inclined along the distribution direction of volcanic rock strata, which is consistent with the distribution mode of volcanic reservoirs.

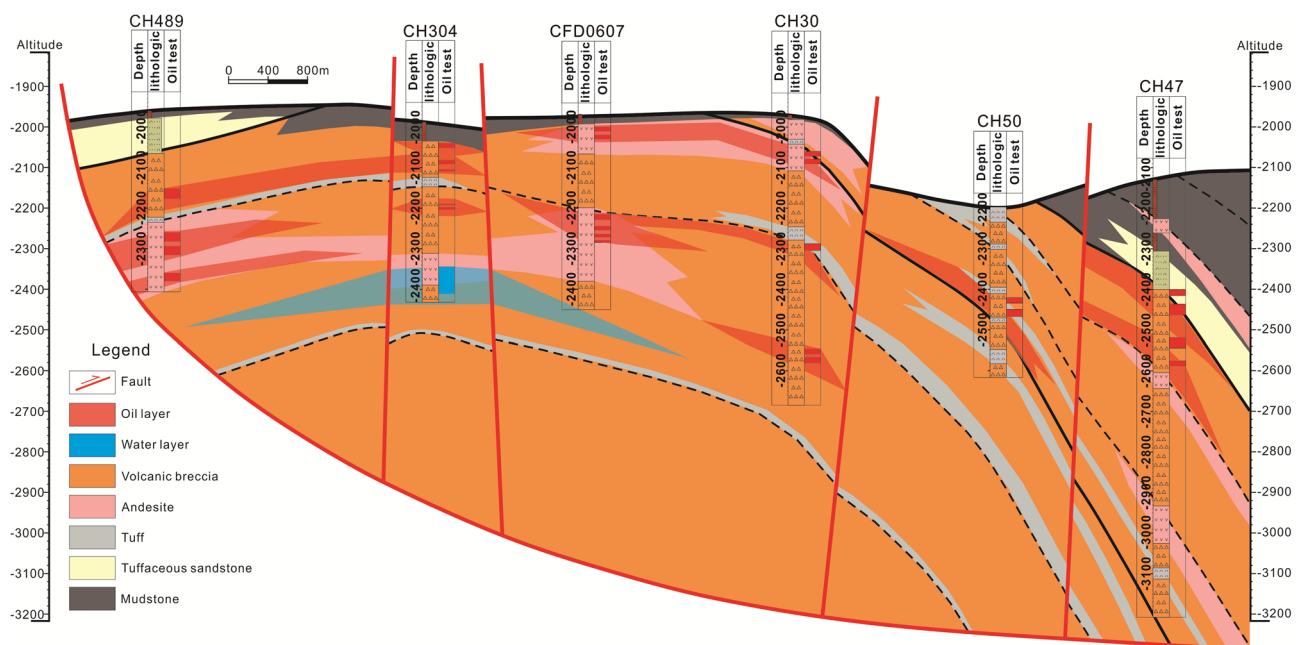


Figure 8: Through CH489-CH47 well oil layer contrast diagram (A-A').

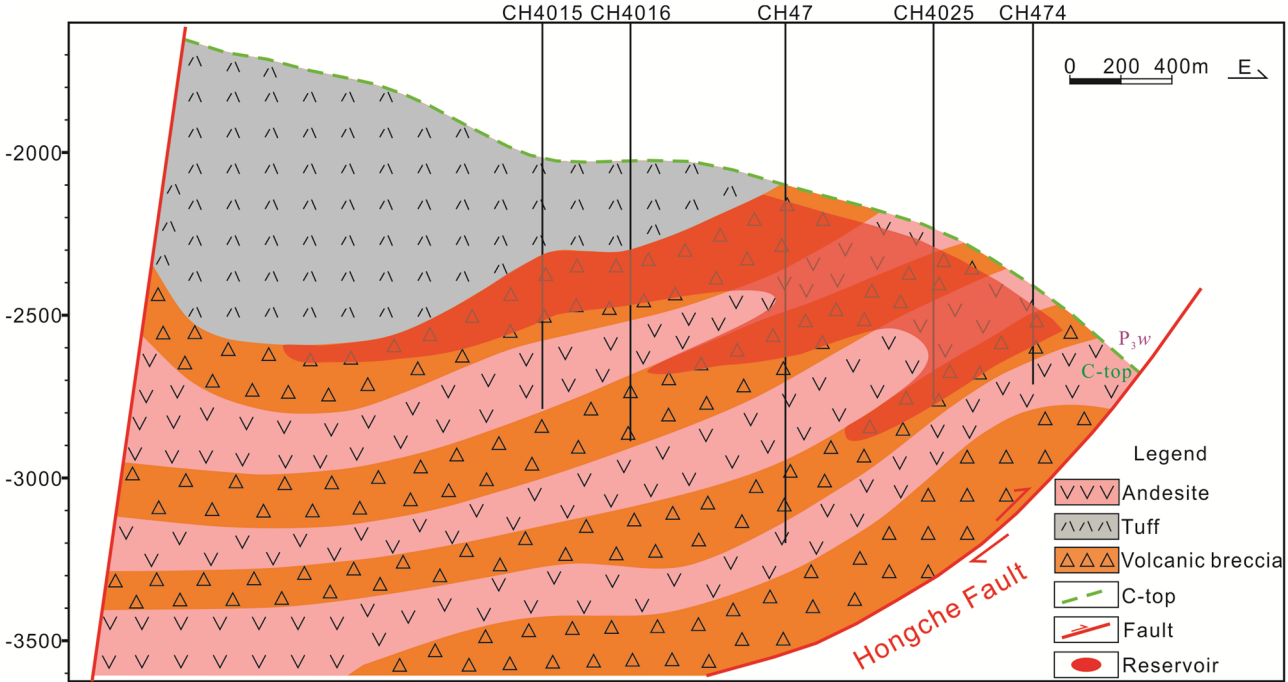


Figure 9: The distribution pattern of CH4015-CH474 reservoir (B-B').

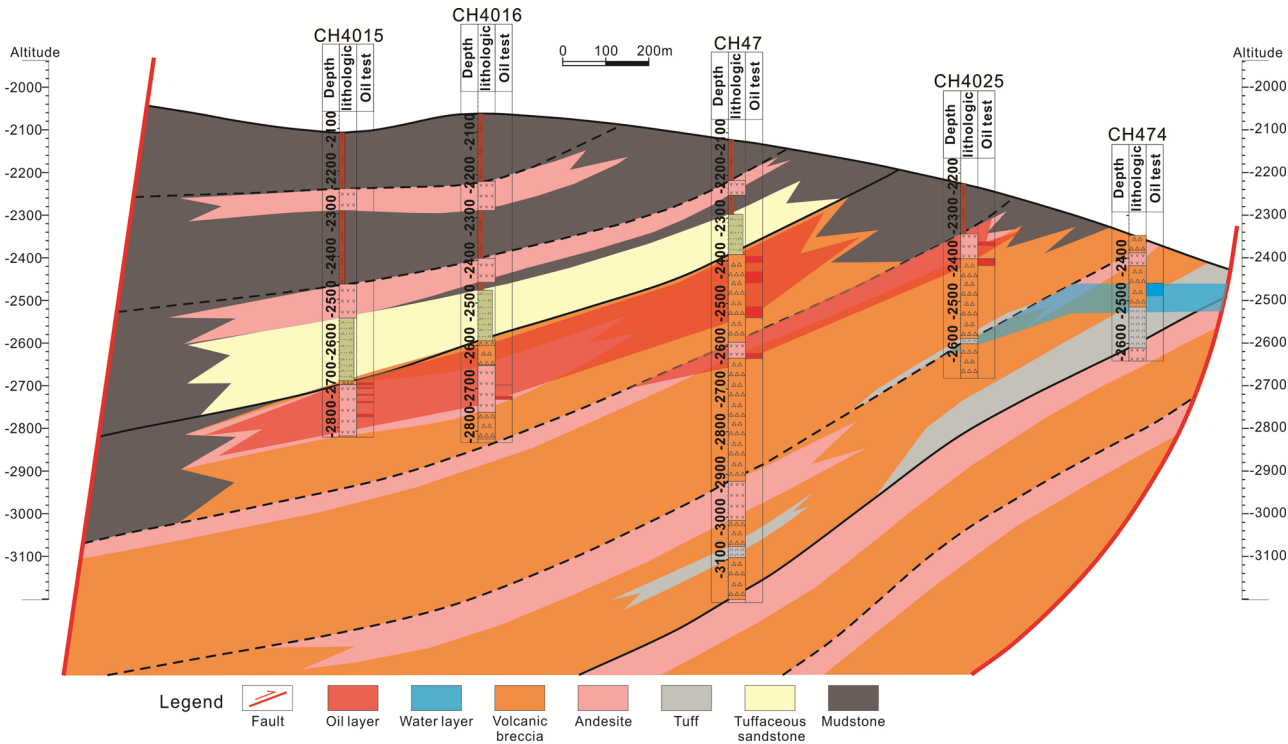


Figure 10: Through CH4015-CH474 well oil layer contrast diagram (B-B').

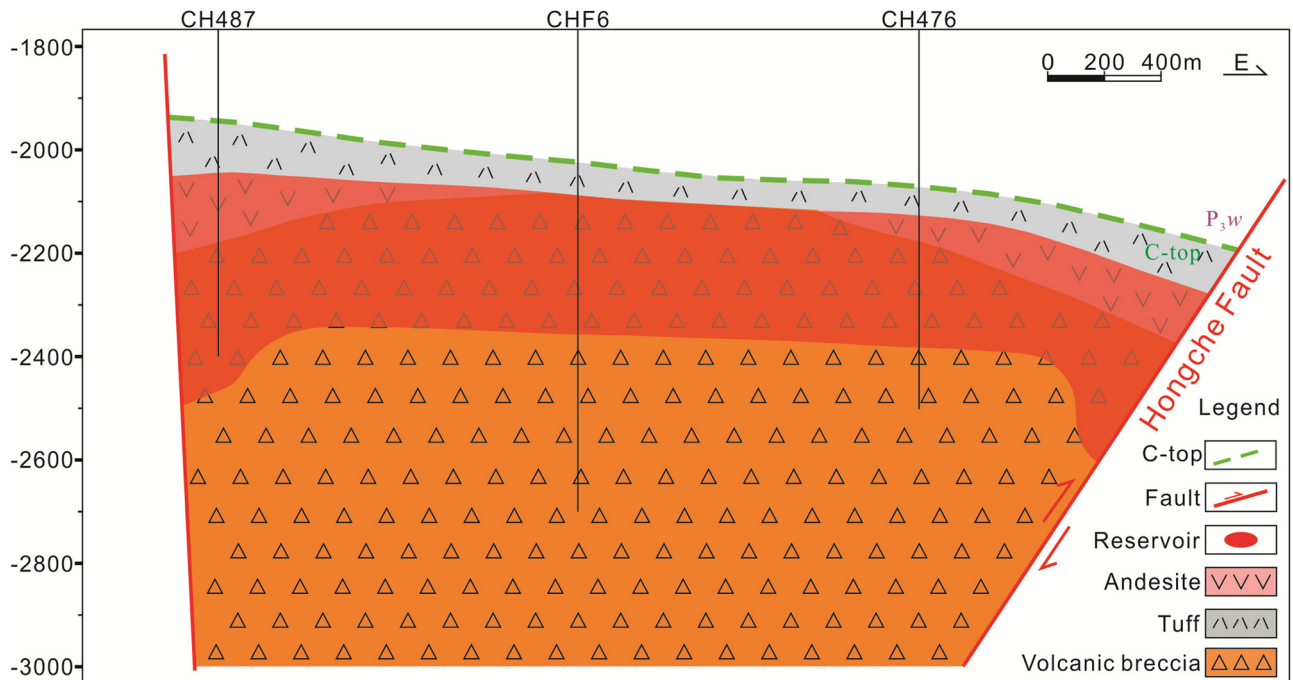


Figure 11: The distribution pattern of CH487-CH476 reservoir (C-C').

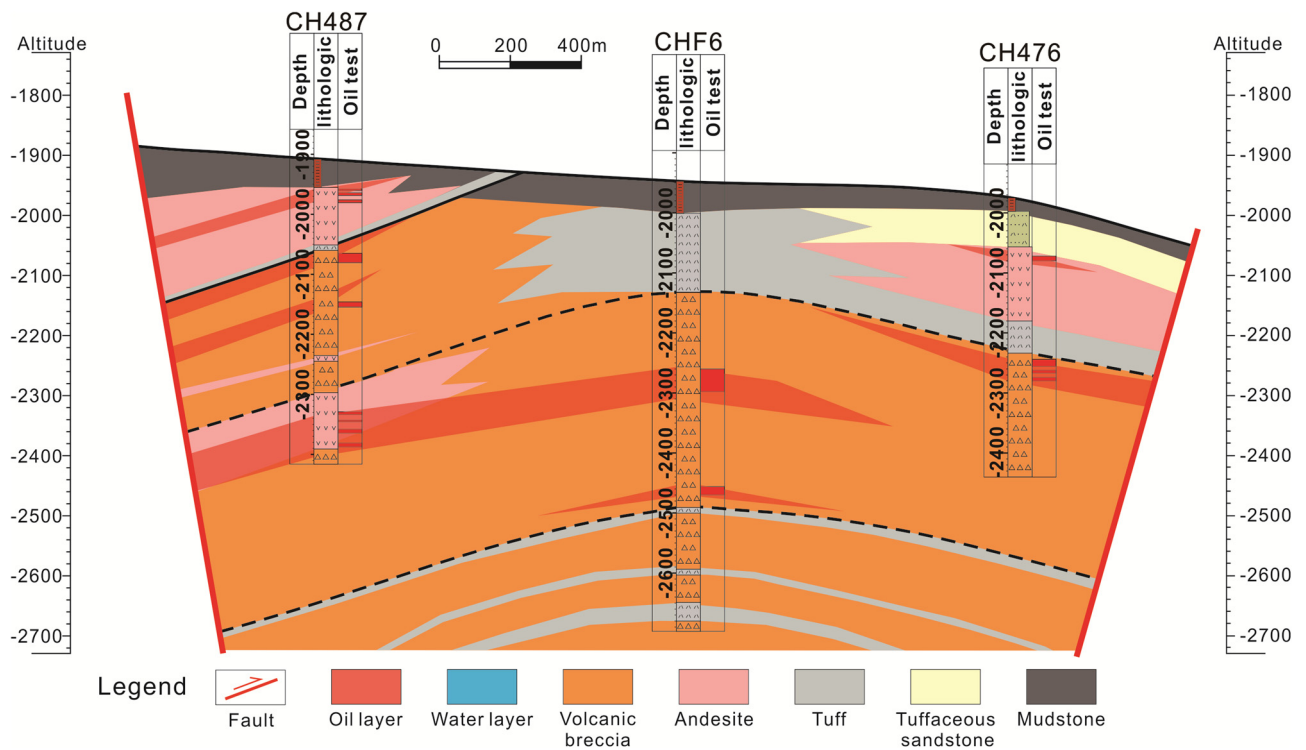


Figure 12: Through CH487-CH476 well oil layer contrast diagram (C-C').

5.2.3 Comparative analysis of the east-west reservoir (southern study area)

The vertical distribution of the east-west volcanic reservoir in the southern part of the study area shows that (Figure 11) the southern section contains a large set of thick volcanic breccia accumulation bodies, which do not have stratification and cannot be used to assess the occurrence and shape of the rock mass. Due to the strong heterogeneity inside the accumulation body of the volcanic breccia, the fracture development degree and the degree of weathering and denudation in different structural parts are different, which leads to great differences in the physical properties and a lack of constraint of lithology on the reservoir distribution. Therefore, the distribution of volcanic reservoirs in the south is not affected by lithological factors and is mainly controlled by the development of faults (fractures) and weathering denudation [53–57], distributed within approximately 400 m from the top of the weathering crust.

The comparison of east-west wells in the southern part of the study area shows that the oil layer is not affected by the lithology distribution and is more inclined because of the oil-bearing blocks (Figure 12). This result is consistent with the reservoir distribution model.

5.3 Relationship between tectonic evolution and volcanic reservoir distribution

The formation of volcanic reservoirs is more dependent on post-transformation. Although the strength and weathering resistance of different lithologies are different, as long as the degree of post-transformation is high enough, volcanic rocks may form effective reservoirs. Structure plays a dominant role in the later transformation of volcanic reservoirs. Structural activities control the development of faults (fractures), promote the generation of weathering, affect the distribution of lithology to a certain extent, and affect the formation of reservoirs, making them an important basis for forming volcanic reservoirs [58–61]. The formation and distribution of Carboniferous volcanic reservoirs in this study area are closely related to the tectonic activity and evolution of the Hongche fault zone in the northwestern margin of the Junggar Basin, mainly shown by the following points.

First, the formation and distribution are accompanied by tectonic movement, which produces many fractures. After the formation of Carboniferous volcanic rocks, affected by the activity of the Hongche fault zone, tensile fractures began to occur based on the tensile background of the early Permian. At

the end of the early Permian, the stress field was transformed into compression, forming a thrust nappe structure. The internal shear fractures began to develop in large numbers, and tensile fractures developed at the transitional end of the volcanic nappe. The Triassic period was further strengthened based on the previous structural pattern, which expanded the scale of the fractures that formed in the early stage and produced new structural fractures. The development of fractures effectively improved the permeability of volcanic reservoirs, increased the reservoir space, and provided infiltration channels for surface water in the later weathering process, further improving the physical properties of volcanic rocks, thus laying the foundation for forming volcanic reservoirs.

Second, tectonic uplift promoted weathering and leaching. The Carboniferous volcanic rocks in the study area were uplifted and eroded under the control of the Hongche fault thrust nappe structure, and the weathering crust formed at the top. In the process of weathering and leaching, the soluble minerals in volcanic rocks were dissolved to form various dissolution pores, and some structural fractures were expanded by fluid dissolution to form dissolution fractures. Thus, the physical properties of volcanic rocks within the range of control of the weathering crust were effectively improved, providing conditions for reservoir formation.

Finally, the structural form has a certain influence on the distribution of the rock mass. The Carboniferous volcanic rock mass was subjected to a thrust nappe structure, forming a high-angle tilt, and some reservoirs developed along the dominant lithology, resulting in the reservoir distribution also tilting with the rock mass.

6 Conclusion

Through the interpretation and analysis of seismic data, well correlation, and reservoir distribution data, we have reached the following conclusions:

(1) In the early stage of thrust nappe formation, the strata began to be affected by extrusion, the volcanic rock mass was slightly deformed, and shear fractures were generated internally. In the middle stage of the thrust nappe, thrust faults were formed, high-angle deformation occurred in the volcanic rock mass, internal cracks were further developed, and tensile cracks began to develop at the transitional end. They were uplifted to accept weathering and leaching, and the weathering crust was formed at the top. In the late thrust nappe stage, the strata began to decline and accept deposition. The Carboniferous volcanic rocks were finalized, and there was no large-scale transformation in the later stage.

(2) There are differences in volcanic reservoirs in the northern and southern parts of the study area. The northern part is located at the edge of the eruption center, the rock mass is stratified, and the inclination of the volcanic rock mass constrains the reservoir. To a certain extent, the reservoir develops along the distribution of volcanic rock mass and belongs to the “reformed” reservoir, mainly controlled by fractures and lithology. The south is located in the center of the volcanic eruption, and the rock mass has poor stratification and is not controlled by the lithology distribution. The southern reservoir is mainly controlled by weathering leaching and belongs to the weathered crust-type volcanic rock reservoir.

(3) The formation of high-quality reservoirs in volcanic rocks is more dependent on post-transformation, and tectonic evolution controls the whole process of post-transformation. The tectonic movement caused a large number of cracks in the volcanic rock mass, thus improving the lack of connectivity of the primary pores in the volcanic rock reservoir. Tectonic uplift caused the volcanic rock mass to be reformed by weathering and leaching for a long time to form a weathering crust, which further improved the reservoir's physical properties. The distribution of the reservoir-dominant lithology is affected by tectonic evolution to a certain extent, thus restricting the range of distribution of reservoirs. The evolution model of volcanic reservoirs under the background of thrust nappe structure has a good reference significance for developing volcanic reservoir in the Hongche fault zone. At the same time, it can provide a reference for exploring similar areas.

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