

Characteristics and controlling factors of deep-seated reservoir: a case study from the Fukang Sag of Junggar Basin

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Abstract The characteristics and formation mechanism of clastic reservoirs have a significant impact on petroleum accumulation in the deep-seated strata of sedimentary basins. Newly drill data indicate that the tight reservoirs in the lower slope of Fukang Sag in the Junggar Basin produce a lot of oil despite being buried extremely deep and with low porosity. By using lithological and geochemical studies, we investigated the formation of these deep-seated reservoirs through the comparison between upper and lower slopes. The results suggest that the reservoir of lower slope is highly compacted and has weaker dissolution than the reservoir in the upper slope. Dissolution and micro fractures are the key factors in determining the formation of deep-seated reservoirs. The fluids that caused the dissolution of reservoir can be divided into three stages and sourced from the mixture of deep and basin fluids. A model of reservoir formation and evolution has been set up. Our research could provide an insight for the formation of deep-seated reservoirs in similar geological conditions worldwide.

Keywords Junggar Basin, Fukang Sag, Wuerhe Formation, reservoir, evolution

1 Introduction

Deep-seated clastic reservoirs are one of the important new frontiers in formation of petroleum accumulation and

attract much attention in recent years (Eichhubl et al., 2009; Armitage et al., 2010; Xi et al., 2015a; Yan et al., 2018; Zhang et al., 2020). Many studies were conducted on the reservoir basic characteristics, physical characteristics, diagenesis and formation mechanisms (Folk, 1980; Chen et al., 2001; Wang et al., 2013; Xi et al., 2015b; Gao et al., 2019; Hu et al., 2021; Cao et al., 2022). Different with the regular clastic reservoirs, the deep-seated reservoirs are tighter with small porosity and permeability (Higgs et al., 2007; Duan et al., 2017; Wang et al., 2018; Chen et al., 2022). The reason for the reduction of reservoir physical properties is complex, including the physical and geochemical diagenesis (Sadegh et al., 2008; Zhou et al., 2016). The original grains would be rearranged, distorted, transformed and disappeared and new minerals could growth and recrystallization during these processes. Compaction, quartz overgrowth, and carbonate minerals cementation are considered as the most important factors to control the reduction of porosity and permeability of reservoirs (Salem et al., 2000; Liu et al., 2020; Qin et al., 2021; Li et al., 2022). The formation of different structures, such as faults, fractures and regional tectonic activities, can cause the changes in the diagenetic system (Gale et al., 2004; Olson et al., 2007; Olson et al., 2009). They not only change the diagenetic conditions and the way of clay minerals connection, but also affect the reservoir structures, due to the materials bring in and out (Laubach and Ward, 2006; Lavenu et al., 2014). Dissolution may be the key factors in controlling the formation of good quality tight reservoir (Li et al., 2018; Yuan et al., 2019; Hale et al., 2022). Variety types of secondary pores were found in the clastic rocks, including the pores between

Received June 28, 2023; accepted May 6, 2024

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and in the grains, minor pores in the authigenic and diagenetic clays and micro fractures (Ehrlich et al., 1991; Yuan et al., 2019). The feldspar, chert, lithic fragment and carbonate cementation are the main positions to host these secondary pores (Schmidt et al., 1977; Shanmugam, 1985; Harris, 1989; Yuan et al., 2019). Although many studies have been conducted on the formation of tight reservoirs, the main controlling factors and diagenetic evolution processes of deep-seated clastic reservoir is still confused and whether the deep-seated strata can develop large scale reservoir or not is questionable.

The Fukang Sag in the Junggar Basin is a significant potential area for petroleum accumulation in the deep-seated reservoir, making it an ideal location for investigating reservoir characteristics and their formation mechanisms. Recent petroleum exploration has indicated that the east edge of Fukang Sag is a gentle slope, and the lower slope's strata can host substantial petroleum resources, even their porosity and permeability are extremely low (He et al., 2021). Understanding this phenomenon is crucial for deep-seated strata exploration. One of the key aspects to constrain the petroleum exploration is the development of reservoir characteristics. Hence, employing lithology and mineralogy methods, we conducted a comparative analysis of the reservoir characteristics between the upper and lower slopes of the east margin of Fukang Sag. Additionally, we discussed the formation mechanisms and evolution of these reservoirs.

2 Geological setting

The Junggar Basin, located in the northern part of Xinjiang, is an important component of the basin and range system in Xinjiang. The basin has an area of approximately 130000 km². The basin is surrounded by folded mountain ranges, forming a triangular shape. The north-western edge is bordered by the Zaire and Hala' alate mountains, the north-eastern edge is bordered by the Altai, Qinggeli and Kelameili Mountains, and the southern edge is bordered by the Bogda and Yilinheibiergen of the Tianshan Mountains. The basin is delineated from the surrounding mountain ranges by thrust faults and has formed foreland basins in front of the mountains in different edges. The Junggar Basin is a large Late Paleozoic-Mesozoic compressional and superimposed basin (Wu et al., 2004), and it has undergone complex tectonic evolution since its formation. However, most of the studies tend to show that the evolution of this basin can be divided into three large stages, including: 1) the initial formation stage in the Late Carboniferous; 2) the intracontinental depression development stage in the Mesozoic; and 3) the rejuvenated foreland basin development stage from the Neogene to the Quaternary (Tang et al., 1997; Qiu et al., 2002; Zhu et al., 2012).

The Fukang Sag is located in the south-eastern part of the Junggar Basin. It is bordered to the east by the Beisantai Uplift, to the south by the Fukang thrust belt, and to the north by the Baijiahai Uplift (Fig. 1). Its tectonic evolution characteristics are closely related to the formation and evolution of the surrounding uplift belts. Multiple stages of strata overlap have developed toward the uplift belts. The exploration area is approximately 10,000 km², with a low level of exploration. It is an important area for the exploration of large-scale oil and gas reserves in the "near-source area".

3 Data and methods

To compare the reservoir differences in upper and lower slope, all samples were selected in the same Wuerhe Formation of Permian in the east margin of Fukang Sag, including 60-two samples from ten wells. Many other data, such as porosity, permeability, and so on, were collected from the Xinjiang Oilfield. Comprehensive application of regional geological, well logging and drilling core data is used to systematically reveal the characteristics of reservoirs and their formation mechanism in the study area. Reservoir petrology and diagenetic studies are conducted through analyses of reservoir spatial types, diagenetic events, and reservoir heterogeneity. Based on these studies, a development model for high-quality deep burial reservoirs in the study area is established. Petrology, X-Ray Powder Diffraction (XRD) and scanning electron microscopy are conducted at the State Key Laboratory of Deep Oil and Gas of China University of Petroleum (East China).

4 Results

4.1 Reservoir comprehensive characterization

4.1.1 General reservoir characteristics

Reservoir is one of the important controlling factors for oil and gas accumulation. The reservoir's petrophysical properties and pore structure are the fundamental indicators for identifying reservoir storage and permeability, as well as the most direct parameters for evaluating oil and gas reservoirs. In the exploration and development of oil and gas fields, reservoir characteristics serve as the main basis for estimating well productivity and recovery rates. Lithological and petrological studies were conducted to reflect the reservoir characteristics of Wuerhe Formation in the Fukang Sag (Figs. 2 to 6).

The characteristics of these reservoir exhibit strong heterogeneity. By comprehensively utilizing more than 200 cores and data on physical properties within the study area, the reservoir characterization generally reveals the

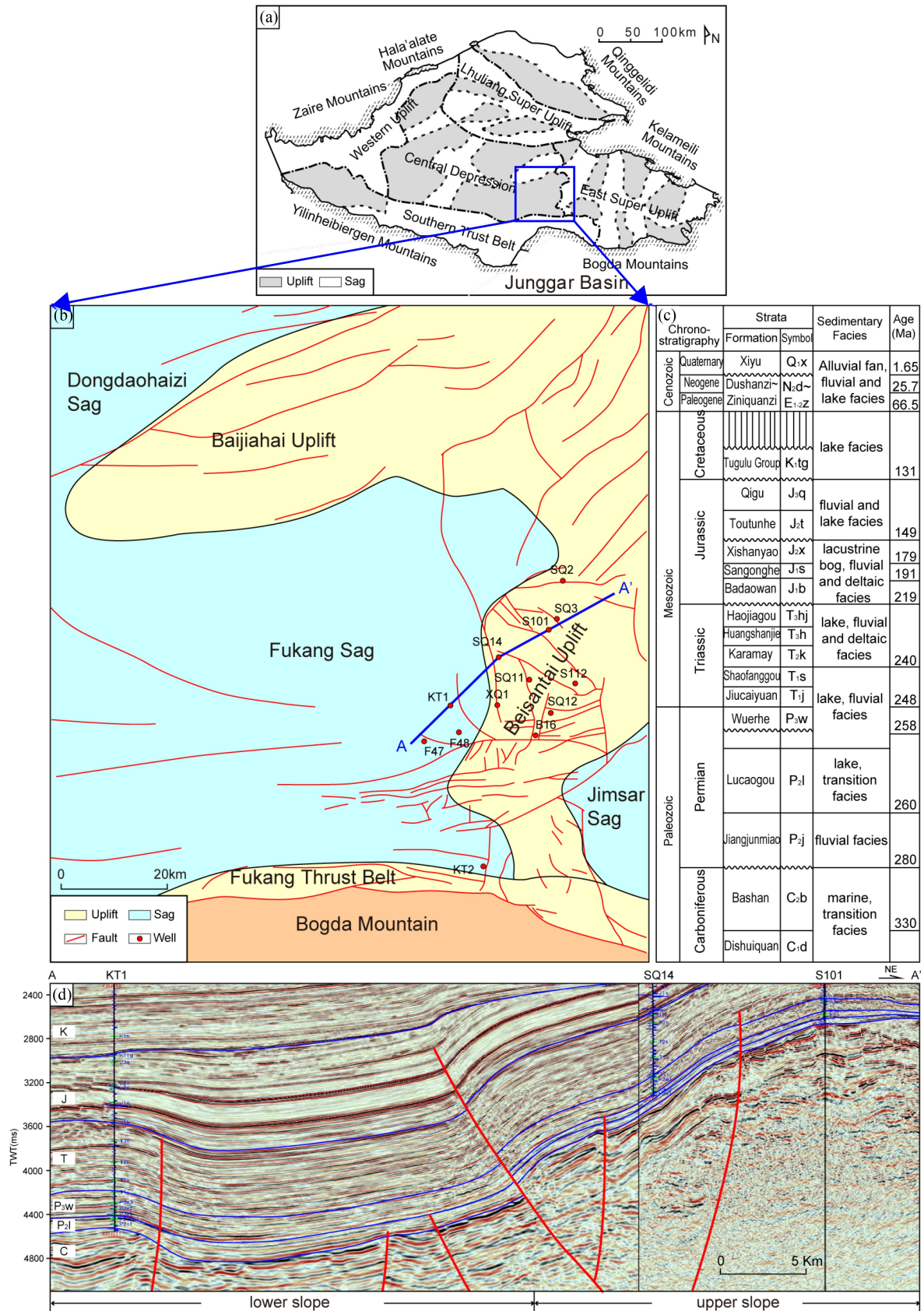


Fig. 1 Maps show the location (a), fault system (b), stratigraphic column (c), and division of upper and lower slope of east margin of Fukang Sag (d), Junggar Basin.

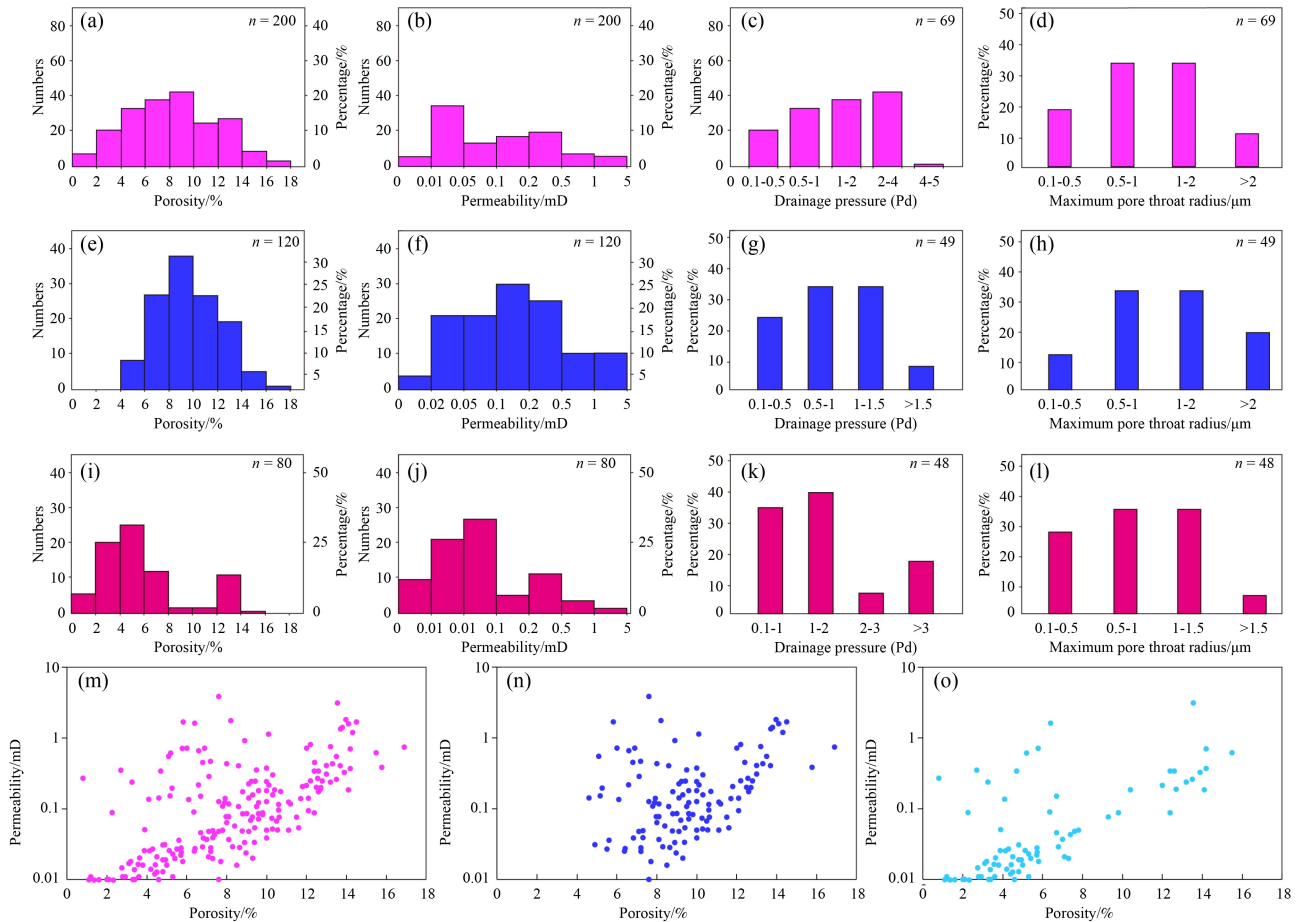


Fig. 2 Reservoir physical characteristics of Permian Wuerhe Formation in the study area. (a–d) are the total reservoir physical column of Wuerhe Formation. (e–h) are the reservoir physical column of Wuerhe Formation in upper slope. (i–l) are the reservoir physical column of Wuerhe Formation in lower slope. (m, n, and o) plots show the relationship between porosity and permeability in the total Wuerhe Formation, upper and lower slope, respectively.

following information (Figs. 2(a)–2(l)): the maximum porosity of the reservoir in the study area is 16.9%, the minimum is 0.8%, and the average is 8.17%; the maximum permeability ranges from 3.87 mD to 0.01 mD, with an average of 0.26 mD. The pressure range for reservoir displacement ranges from 0.16 Pd to 4.09 Pd, with an average of 1.14 Pd. The maximum pore throat radius of the reservoir is concentrated between 0.5 μm and 2 μm . Moreover, there is a certain positive correlation between porosity and permeability (Figs. 2(m)–2(o)).

Due to different environments, there are differences in mineral composition, particle size, and structural features of the original sedimentary materials. The reservoirs in the upper and lower slope have undergone completely different tectonic evolution processes and exhibit significant differences in burial depth. Specifically, the average burial depth of reservoirs in the upper slope is around 2800 m, while in the lower slope, it is around 4700 m.

4.1.2 Upper slope

The rock types of the reservoir in the upper slope are

mainly litharenite, including arenaceous conglomerate and coarse sandstone (Figs. 3(a)–3(d)). The lithofacies sorting is moderate to poor, and the particles are mostly sub-angular. The primary contact between rock particles is characterized by point-to-point and point-to-line. In terms of sedimentary features, scour surfaces and blocky structures are commonly observed, with wedge-shaped and tabular cross-bedding developed. Among them, erosion surface are the most common sedimentary structures in this area, formed by the erosion of underlying sediment surfaces in strong water currents. They appear as uneven surfaces with conglomerates and conglomeratic sandstones deposited on top of mudstones and silty mudstones, often containing mud pebble and torn mud fragments. Erosion surface are generally developed at the bottom of river channels, and when multiple abandoned river channels are superimposed, several pebble-bearing layers can be seen. Blocky bedding is commonly developed in conglomerates and sandstones, appearing as large segments of conglomerates or sandstones with no differentiation in composition and structure. The pebbles in conglomerates are randomly distributed without clear directional arrangement or grain-

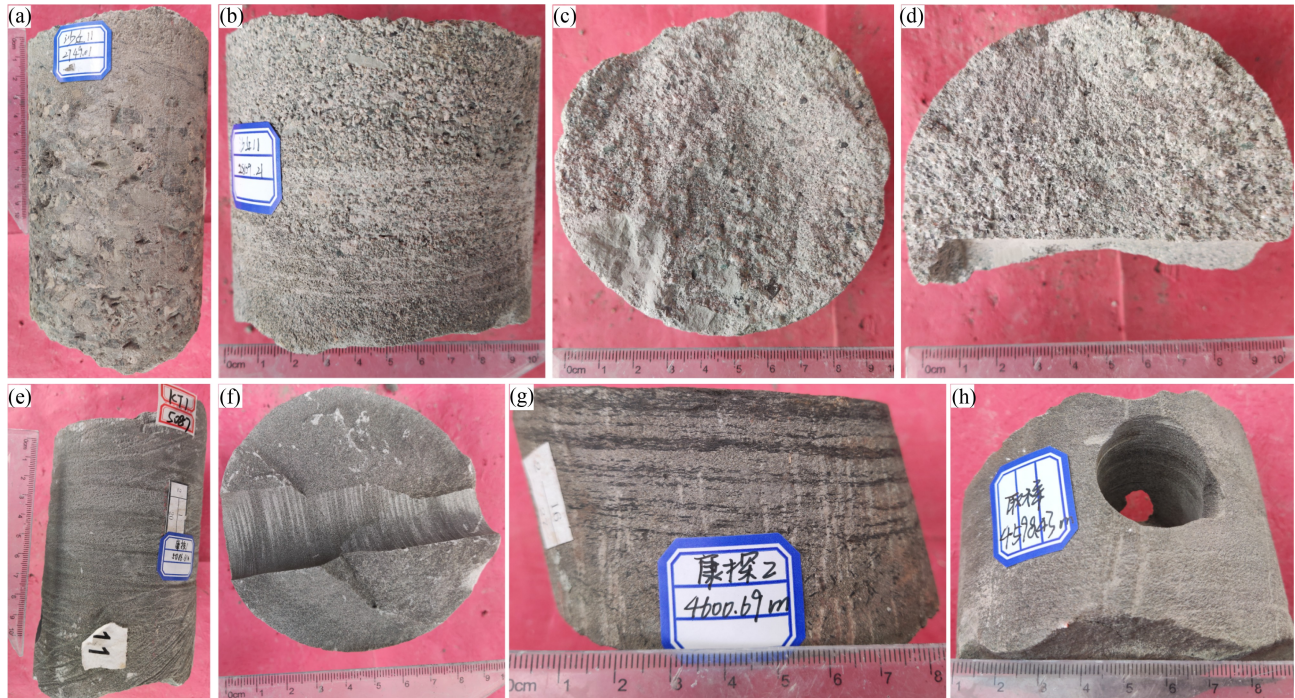


Fig. 3 Photos show the drill cores of the Wuerhe Formation of Permian. (a–d) are from the upper slope and e–h are from the lower slope. (a) SQ11, 2749.0 m, uneven sandstones with pebble; (b) SQ11, 2809.2 m, coarse sandstone; (c) SQ12, 2923.2 m, coarse sandstone; (d) SQ12, 2924.1 m, coarse sandstone; (e) KT1, 5086.6 m, silty medium-fine sandstone; (f) KT1, 5086.1 m, fine sandstone; (g) KT2, 4600.69 m, silty medium-fine sandstone; (h) KT2, 4598.03 m, fine sandstone.

size variation. Blocky bedding in sandstones is generally formed by strong bioturbation disrupting the primary sedimentary structure. Grain-size variation bedding mainly exhibits normal grain-size variation bedding, although rare examples of reverse grain-size variation bedding can be found in some wells. It is commonly found above erosion surfaces and is characterized by the gradual decrease in the size and content of gravel and mud gravel upwards in conglomerate and sandstone layers, transitioning from conglomerates to conglomeratic sandstones, sandstones, silty sandstones, and mudstones, reflecting the sedimentation process from strong to weak hydraulic forces.

XRD test results indicate that the main mineral components of the reservoir are quartz, plagioclase feldspar, calcite, and clay minerals (Figs. 4(a) and 4(b)). Quartz content is greater than 50%, followed by plagioclase feldspar and clay minerals, with contents reaching 19% and 14% respectively. Carbonate minerals (calcite + dolomite + magnesite) are present in high amounts. There is significant variation in clay mineral content, with the B16 well sample mainly composed of illite-montmorillonite interstratification, while the SQ12 well sample has a high content of chlorite.

In the upper slope, the primary intergranular porosity in the Permian Wuerhe Formation is rare, and the diagenetic stage has experienced multiple periods of varying degrees of dissolution, resulting in the development of numerous intragranular and intergranular dissolution pores. For example, in Well SQ 12, sample 2921.3 m exhibits strong

carbonate cementation, with cement filling the intergranular pores or forming a rind around the grains, mainly composed of calcite and siderite (Fig. 5(a)). At 2114.0 m in well B16 and 2872.8 m in well SQ11 (Figs. 5(b) and 5(c)), intragranular dissolution pores dominated by feldspar particles are observed. At 2874.0 m in well SQ11, intergranular pores are developed (Fig. 5(d)). Coexistence of intragranular and intergranular dissolution pores can be observed at 2872.8 m in well SQ11 and 2923.4 m in well SQ12 (Figs. 5(e) and 5(f)). In the upper slope, a small number of fractures can be seen in the reservoir. Fractures are often highly developed in conglomerate and sandstone reservoirs, some of which are not filled. These unfilled structural fractures not only serve as reservoirs for oil and gas accumulation, but also provide favorable pathways for fluid migration. Therefore, they play an important role in improving the physical properties, especially permeability, of the study area reservoirs. Based on image recognition, the porosity range of the reservoir in the upper slope is estimated to be between 3.6% and 8.7%.

The porosity and permeability data of the reservoir (120 samples) show that the maximum porosity value is 16.9%, the minimum is 4.6%, and the average is 9.58% (Fig. 2(e)). The highest frequency of samples range from 8%–10%, accounting for approximately 40% of the total. The frequencies for the 6%–8% and 10%–12% ranges are both around 26%, while the 4%–6% range has a frequency of approximately 8%, and the 16%–18% range has a frequency of about 1%. The maximum permeability

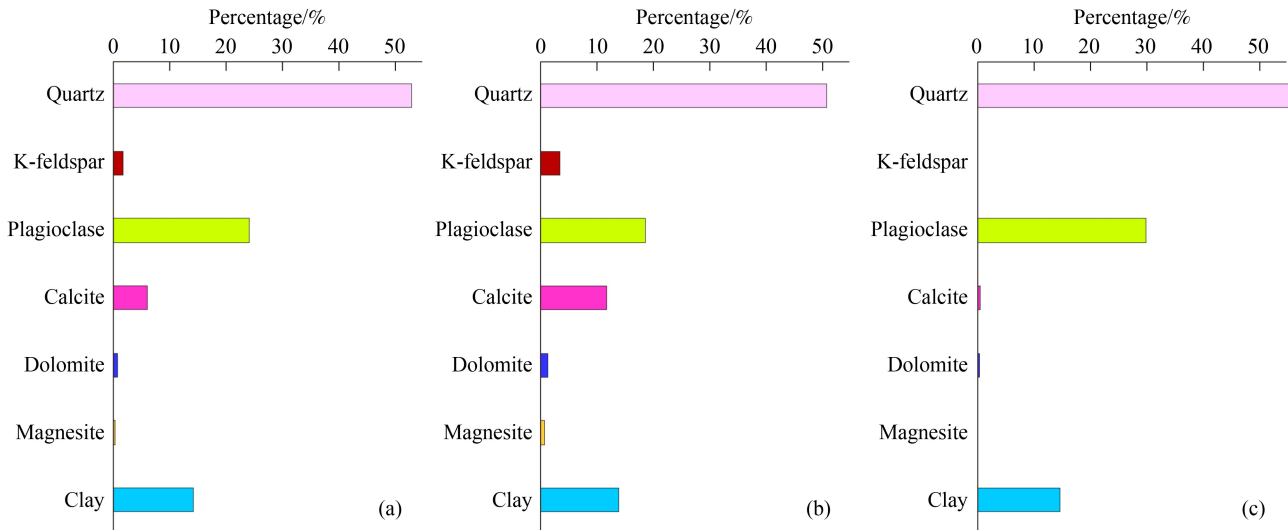


Fig. 4 XRD diagrams show the main contents of minerals in the total Wuerhe Formation (a), upper (b) and lower slope (c) of east margin of Fukang Sag.

value is 3.87 mD, the minimum is less than 0.01 mD, and the average is 0.32 mD (Fig. 2(f)). The highest frequency of samples is within the 0.1–0.2 mD range, accounting for nearly 30% of the total. The frequencies for the 0.02–0.1 mD and 0.2–0.5 mD ranges are both above 20%. The pore structure characteristics of the reservoir in the upper slope show the frequency of drainage pressure is high in the interval of 0.5–1 Pd and 1–1.5 Pd, both of which are about 35%, while the frequency of samples with more than 1.5 Pd is less than 10% (Fig. 2(g)). The samples with the mercury removal efficiency of 20%–30% are absolutely superior, and the frequency is more than 50%. The maximum pore throat radius was concentrated in the range of 0.5–2 μm (Fig. 2(h)). From the porosity-permeability diagrams, it can be seen that there is a good correlation between porosity and permeability when the porosity is greater than 8% (Fig. 2(n)).

4.1.3 Lower slope

The lithology of the reservoir in the lower slope mainly consist of fine sandstone, heterogeneous sandstone, and silt-bearing medium-fine sandstone (Figs. 3(e) to 3(h)). Compared to the reservoir in the upper slope, the sandstone has finer grain size. The rock particles are moderately sorted and mostly appear as subrounded and subangular shapes. The predominant contact relationship between rock particles is linear and concave-convex. Thin interbedded layers of mudstone can be observed between sandstone layers, with the development of horizontal bedding and low-angle cross-bedding. Among them, it is more common in drill cores and generally occurs in fine sandstone and silt-bearing sandstone layers, with a thickness of 5–10 cm and a dip angle of $10^\circ \pm$. The grain size variation within the laminations exhibits inverse rhythmic or composite rhythmic patterns. In the F48 well,

occasional carbonate cementation can be seen in the intergranular pores.

XRD test results indicate that the predominant minerals in the reservoir of the lower slope are quartz, plagioclase feldspar, and clay minerals (Fig. 4(c)). Quartz accounts for approximately 55% of the composition, followed by plagioclase feldspar and clay minerals with contents of about 30% and 15%, respectively. The samples almost lack carbonate minerals (calcite + dolomite + magnesite). The contents of clay mineral shows little variation and is composed of illite, kaolinite, chlorite, and interlayered montmorillonite. The difference is that the samples in F48 well are mainly composed of interlayered montmorillonite, while the KT2 well has the highest content of chlorite.

In the reservoir of the lower slope, primary intergranular pores are rare, but a large number of intragranular and intergranular dissolution pores are developed (Figs. 5(g) and 5(h)). Compared to the reservoir in the upper slope, intragranular dissolution pores are more developed. For example, in the KT2 well at 4600.7 m, dissolution pores formed by the complete dissolution of feldspar grains can be observed. Fractures are not well developed and are only present in a small number of samples. Based on image analysis, the estimated porosity of the reservoir in the lower slope is between 1.4% and 3.9%.

4.2 Diagenetic processes

The reservoir of the Wuerhe Formation in the Fukang Sag has undergone complex diagenetic evolution. The main diagenetic processes experienced include compaction, cementation, dissolution, pressure solution, metasomatism, and recrystallization. Among them, compaction, cementation, and dissolution are closely related to the evolution of reservoir porosity.

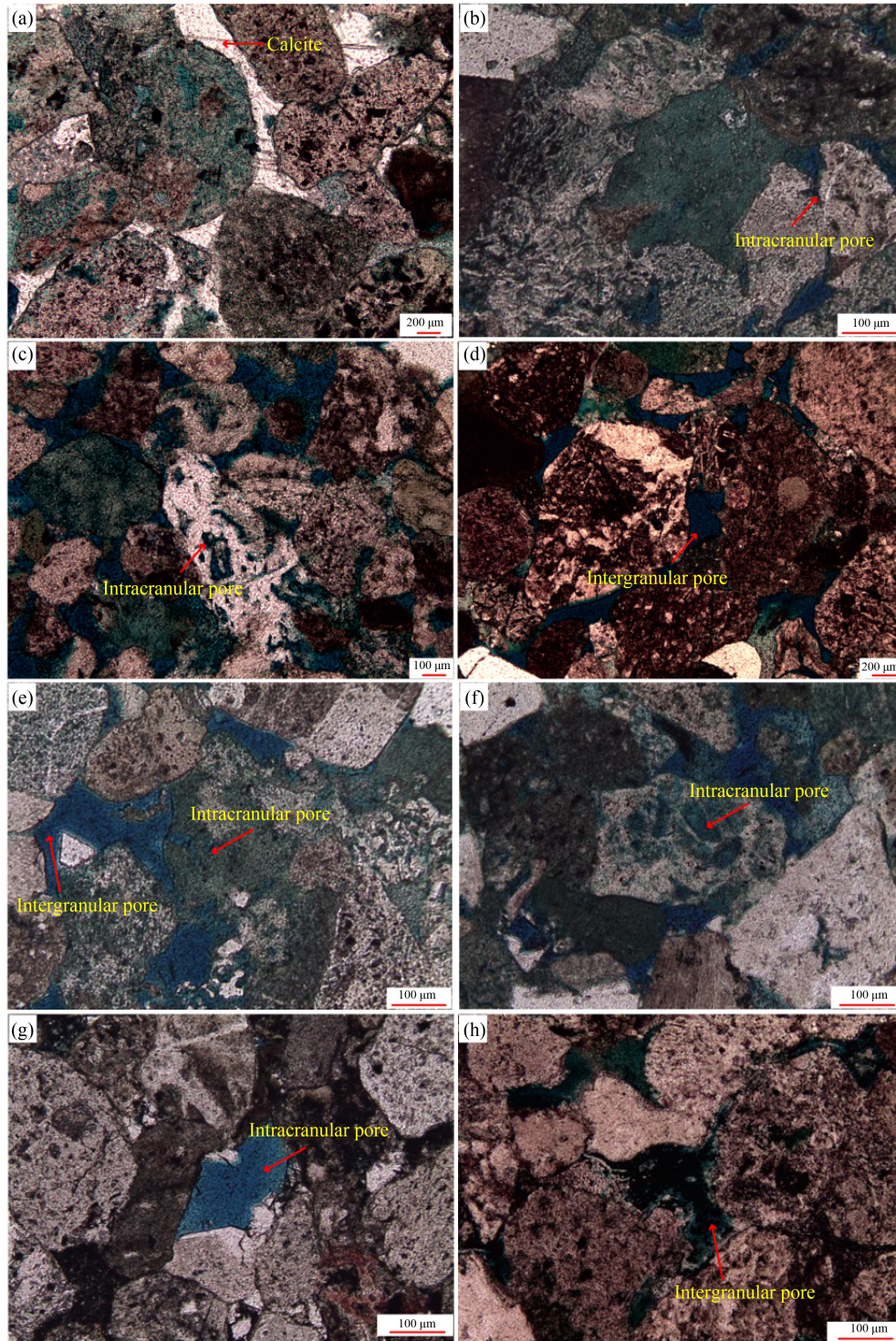


Fig. 5 Microscope photos show the pores in the Wuerhe Formation of Permian. (a–f) are from upper slope and (g–h) are from lower slope. (a) SQ12, 2923.4 m, calcite cements; (b) SQ11, 2872.8 m, intracrystalline pore; (c) B16, 2114.0 m, intracrystalline pore; (d) SQ11, 2874.0 m, intergranular pore; (e) SQ11, 2872.8 m, intracrystalline and intergranular pores; (f) SQ12, 2923.4 m, intracrystalline pore; (g) KT2, 4600.7 m, intracrystalline pore; (h) F48, 4535.2 m, intergranular pore.

4.2.1 Compaction

Mechanical compaction refers to the process where under the influence of overlying sediment and the static pressure of water or tectonic deformation, water is

expelled, sediment particles are tightly packed, and the softer components are squeezed into the pores, resulting in a decrease in pore volume, reduction in porosity, and deterioration of permeability (Wong and Baud, 1999; David et al., 2001; Wong et al., 2004). The characteristics

of compaction are as follows. 1) Particle long axes are oriented. 2) Plastic rock fragments undergo deformation due to compression, biotite undergoes bending deformation, and soft rock fragments are compressed into pseudo-matrix. 3) Rigid particles such as quartz and feldspar contain cracks, which can be filled by later cementing minerals such as anhydrite and calcite. 4) With increasing compaction intensity, particle contacts become tighter, transitioning from floating to point contacts, line contacts, and even local concave-convex contacts. The contact relationships between rock particles are closely related to the content of filling materials. In intervals with high filling material content, compaction is relatively weak, and particles are predominantly supported by basal or suspended contacts. In intervals with low filling material content, line contacts are more common. Extensive analysis of thin sections of core samples indicates that in the upper slope reservoirs of the study area, the dominant contact types between rock particles are point-line contacts and linear contacts, while in the lower slope reservoirs, the dominant contacts between particles are linear contacts and concave-convex contacts (Figs. 6(a) and 6(b)). Statistical analysis of the burial depth of nine wells in the study area shows an average burial depth of 5008 m for the lower slope reservoirs and 3067 m for the upper slope reservoirs; the lower slope reservoirs are significantly deeper than the upper slope reservoirs, which is consistent with the statistical results of particle contact modes in the reservoirs.

4.2.2 Cementation

Cementation refers to the precipitation and crystallization of dissolved components of pore water in sandstone pores, which can cement the detrital sediment into rock (Morad, 1998; Milliken and Curtis, 2016). The main cementing minerals in the sandstones of the Wuerhe Formation in the Fukang Sag include carbonate minerals, silica minerals, clay minerals (zeolite), and iron-bearing minerals. Cementation acts as a destructive process, plugging the pores and reducing porosity.

There are significant differences in cementation between the upper slope reservoirs and the lower slope reservoirs. Specifically, carbonate cementing minerals such as calcite and siderite are commonly found between particles in the upper slope reservoirs. Representative samples from well SQ12 have a high cementation content with an average of 17.3%, indicating the presence of pore-filling and matrix-filling cements (Fig. 5(a)). In the lower slope reservoirs, silica and zeolite cements dominate, and phenomena such as secondary enlargement of quartz grains and silica filling are observed. The zeolite cements are mainly composed of clinoptilolite.

4.2.3 Dissolution

Dissolution refers to the chemical erosion process of soluble rocks by different source of fluids. Reservoir dissolution mainly includes near-syngenetic freshwater dissolution, early diagenetic alkaline water dissolution,

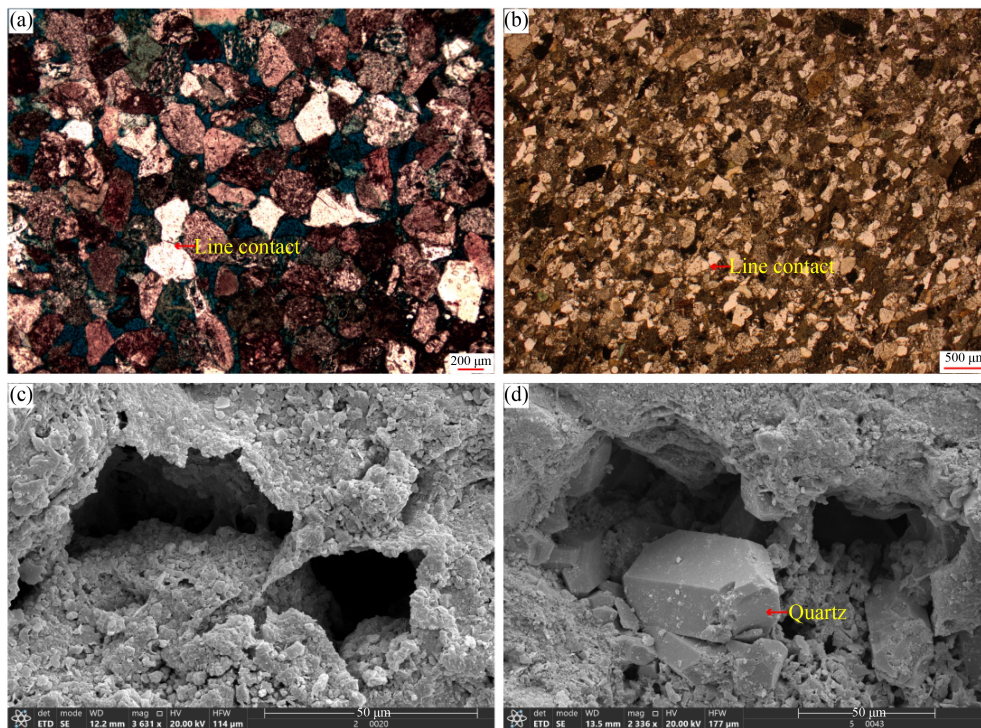


Fig. 6 Microscope photos show the main types of diagenesis in the Wuerhe Formation of Permian. (a) and (c) are from the upper slope, (b) and (d) are from the lower slope. (a) B16, 2119.8 m, the grains are in point-line contact; (b) F48, 4531.2 m, the grains are in line-convex contact; (c) B16, 2119.8 m, intracrystalline pore; (d) KT2, 4601.7 m, intracrystalline pore filled by quartz.

meteoric freshwater dissolution during the surface period, and mid-diagenetic acid water dissolution (Huang and Kiang, 1972; Dietzel, 2000). These processes can improve reservoir pore structure, but the degree of improvement varies for different lithostratigraphic intervals. Observations of thin sections and scanning electron microscopy reveal that dissolution is relatively strong in the upper slope reservoirs, often showing non-selective dissolution, high pore throat ratio, and the formation of larger reservoir spaces (Figs. 5 and 6(c)). In the lower slope reservoirs, dissolution is mainly selective, leading to the formation of relatively independent intergranular and intragranular pores, with quartz and other minerals commonly filling the dissolved cavities (Figs. 5 and 6(d)).

5 Discussions

5.1 Diagenetic Evolution Model

The timing of deep-seated thermal fluid activity can be inferred based on various diagenetic phenomena and mineral evolution characteristics (Nedkvitne et al., 1993; Amel et al., 2015). According to the division of diagenetic stages in clastic rocks in the petroleum and natural gas industry of the People’s Republic of China (SY/T 5477-2003), the diagenetic evolution models for the upper slope and lower slope reservoirs have been established, primarily based on parameters such as paleogeothermal gradient, illite/montmorillonite mixed-layer content ratio, clay mineral assemblages, and development of authigenic minerals (Fig. 7).

Research results show that due to the different processes of sedimentation, tectonic movement, diagenesis, and pore evolution, there are certain differences in the reservoir evolution of the Wuerhe Formation in the upper slope (Fig. 7(a)) and lower slope (Fig. 7(b)).

In the upper slope (Fig. 7(a)), which is closer to the provenance, coarse-grained sediment dominates. It has experienced multiple stages of tectonic activities and is currently at a shallow burial depth. The reservoir has undergone the evolution process of low initial porosity, strong to moderate compaction, moderate to strong cementation and compaction reduction, strong to moderate dissolution and porosity enhancement. The diagenetic stage reaches the Middle Diagenetic A1 substage, and the porosity has decreased from an initial 37.5% to the present 9.6%.

In the lower slope (Fig. 7(b)), which is farther from the provenance, fine-grained sediment predominates. It has undergone continuous subsidence and is currently at a deeper burial depth. The reservoir has undergone the evolution process of high initial porosity, moderate compaction and porosity reduction, moderate to strong cementation and compaction reduction, moderate to weak dissolution and porosity enhancement. The diagenetic stage reaches the Middle Diagenetic A2 substage, and the reservoir exhibits a higher degree of tightness, with the porosity decreasing from an initial 40.5% to the present 8%.

5.2 Development conditions and reservoir formation model of high-quality reservoirs

Based on comprehensive studies of petrology,

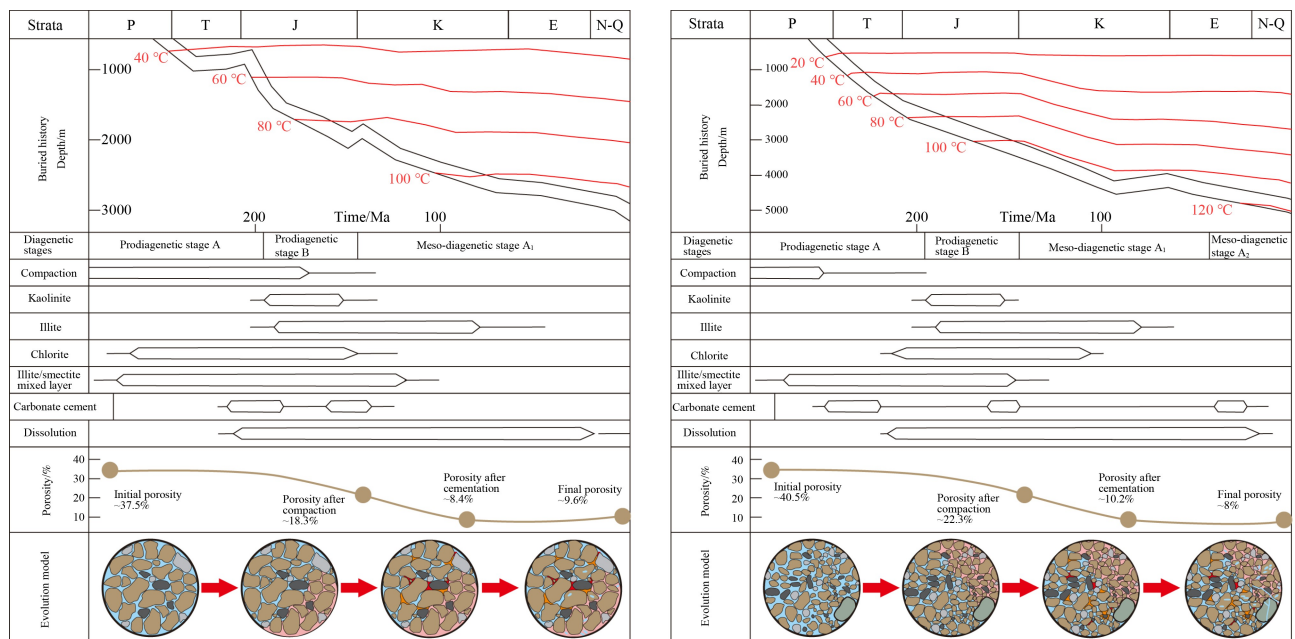


Fig. 7 Diagenetic evolution models of reservoirs in the upper (left) and lower slope (right) of Fukang Basin.

geochemistry, and other factors, the development conditions of reservoirs in the Fukang Sag area have been evaluated. The study suggests that the development of high-quality reservoirs is related to several factors.

1) Dominant sedimentary facies zones

Exploration has confirmed that the subsag fan in the center of Fukang Sag is the largest among all the fans in the fan system of east slope and is the main focus of exploration in the Wuerhe Formation. Thick sand bodies are developed in this zone, and wells such as KT5, F48, F49, and F43 have obtained industrial oil flows. The sedimentary facies zone is characterized by distal sand bars, which are the primary sedimentary facies zones for acquiring deep high-quality reservoirs.

2) Primitive material foundation

Rock studies show that the main lithologies of high-quality reservoirs in the east slope of Fukang Sag are fine sandstone, lithic sandstone, etc., with fine grain size and good sorting. The quartz particle content is relatively high, providing strong resistance to compaction and better preservation of porosity (Pittman and Larese, 1991; Schimmel et al., 2021). The presence of high-quality original sedimentary material provides a material foundation for the development of high-quality reservoirs.

3) Favorable structural positions

Results from physical simulation experiments indicate that temperature is the primary factor influencing dissolution in reservoirs in the lower slope, with albite and clay minerals as the dissolved minerals (Zhi et al., 2019). Drilling results from KT1 well indicate that it is located in a low uplift within the basin in a favorable structural position (Fig. 1). A large number of microfractures, including structural microfractures and microfractures around grains, are developed in the high-quality reservoirs (He et al., 2021). Under the influence of sustained high temperatures, dissolution is expanded by the presence of fractures, providing important conditions for the formation of low-permeability, high-quality reservoirs (Lin et al., 2018; He et al., 2021). Therefore, the reservoirs exhibit relative tightness, frequent fluid activity in the fracture development zone, and better fluid properties. Areas near faults and secondary uplifts within the sag with intense structural activity are key locations for the development of deep high-quality reservoirs.

4) Mixed fluid interactions

Fluid inclusions are more developed in reservoirs in the upper slope, which can be classified into three types: linearly distributed cluster inclusions, enlarged edge inclusions, and isolated intragranular inclusions (unpublished data). The homogenization temperatures indicate two periods of fluid activity: Late Triassic to Early Jurassic and Paleogene to the present (unpublished data). In reservoirs in the lower slope, fluid inclusions are less developed, with no inclusions developed in the

enlarged edges, and a wide range of homogenization temperatures, indicating three periods of fluid activity: Late Triassic to Early Jurassic, Late Jurassic to Early Cretaceous, and Paleogene to the present (unpublished data), consisting with the petroleum charging periods (Zhi et al., 2019). These findings indicate strong fluid mixing in the study area, with more pronounced fluid mixing in the reservoirs of the lower slope. This intense and multi-period fluid activity provides a fluid source and guarantee for the dissolution of deep reservoirs. Our unpublished data also suggest that the fluids that caused the severe dissolution contain large amount of organic acid and various metal cations, such as Mn^{2+} , Fe^{2+} , Na^+ , Ca^{2+} and so on; they were gathered at the rim of authigenic minerals.

5) High pore pressure

Due to intense fluid activity, reservoirs in the lower slope often exhibit higher pore pressures, and overpressure has a significant protective effect on reservoir porosity. The larger the porosity, the stronger the protective effect. When the pore fluid pressure reaches a certain value (approximately 60 MPa, overseas), stress is released in the form of microfractures. Permeability tests on core samples from KT1 well in the Wuerhe Formation of the Fukang Sag show a positive correlation between permeability and experimental pore pressure. As the pore pressure increases, the permeability increases. When the pore pressure reaches a critical value, the permeability increases rapidly, indicating that an increase in pore pressure leads to improved pore structure. It is speculated that high pore pressure can open small throat channels in the reservoir and improve reservoir permeability.

Combined with the evolution history of east margin of Fukang Sag and the above conditions for the development of high-quality reservoirs, a reservoir development model for the eastern part of the Fukang Sag has been constructed (Fig. 8). After the deposition of the Wuerhe Formation, the strata got the initial physical properties. The deposition of Triassic caused the reduction of porosity and permeability due to the compaction. The fluids migrated along the faults started to affect the Wuerhe reservoir, however, the nature of fluids was slightly different in the upper and lower slope. The Fe were more abundant in the upper slope (unpublished data). The organic acid was also mixed into the fluids; however, the dissolution was not obvious. After the deposition of Jurassic, the fluids that migrate along the faults and sandbodies caused the cementation of reservoirs and part of the pores were cemented. From Late Cretaceous to current stage, due to the continuous expelling of hydrocarbon fluids, large amounts of organic acid were mixed into the fluids, leading to the abundant dissolution of reservoir. The reservoirs in the upper slope

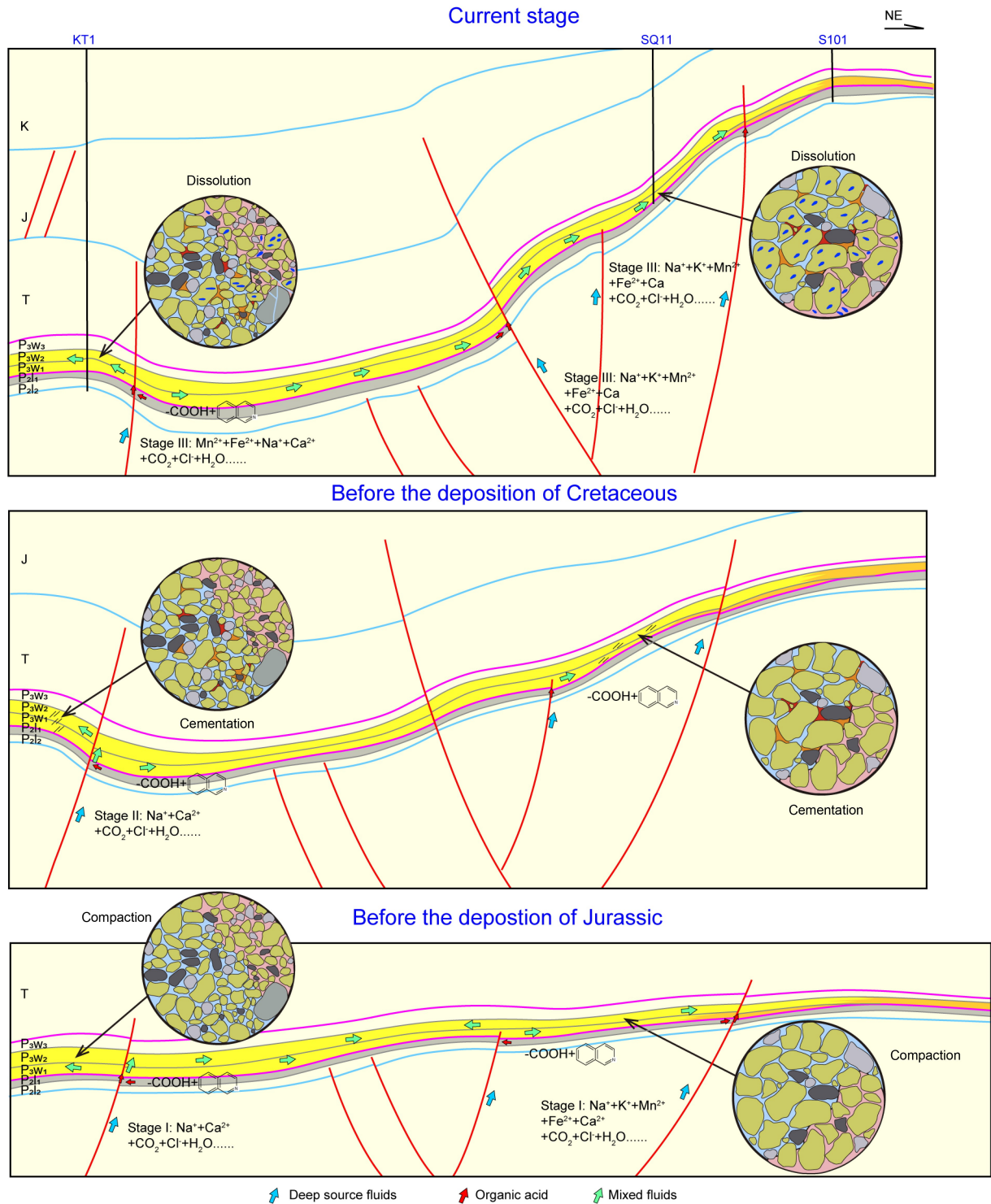


Fig. 8 Reservoir development model of the eastern slope of Fukang Sag. The abbreviation of strata can be found in Fig. 1.

endured more significant dissolution than the lower slope, showing relatively good quality of reservoirs in the upper slope. However, due to the large pore pressure in the lower slope, some microfractures may develop around the grains and the stable pressure can cause these fractures maintain open (He et al., 2021). This process may enable the reservoir to have great ability to host petroleum

though the porosity is low.

6 Conclusions

1) The development characteristics and differences among the reservoirs in the upper and lower slope of the

east margin of Fukang Sag have been studied. Five factors controlled the development of good quality deep-seated reservoirs, including good primary sedimentary facies and primitive material foundation, favorable structural positions, mixed fluid interactions and high pore pressure.

2) The development conditions for high-quality reservoirs in the eastern slope of the Fukang Sag has been studied. A reservoir formation model for high-quality reservoirs was established.

Acknowledgments This research was supported by the PetroChina Science and Technology Major Project (No. 2023ZZ0205), the Scientific research and technology development project of CNPC (Nos. 2021DJ04 and 2021DJ0401), the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA14010301), and the National Natural Science Foundation of China (Grant No. 41702138). We are grateful to the Xinjiang Oilfield Company for providing the data. Thanks for the editors and reviewers for their constructive suggestions.

Competing interests The authors declare that they have no competing interests.

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