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Mechanism of reservoir property variations in deep and ultra-deep sandstones in the Kuqa Depression, China

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ABSTRACT

High industrial gas flows have been obtained in the deep and ultra-deep Bashijiqike sandstones in the Kelasu and Qiulitage structural belts of Kuqa Depression, however, reservoir properties in terms of fracture-pore-throat systems are significantly varied in the different structural belts. Laboratory tests (cores, thin sections, scanning electron microscopy (SEM), nuclear magnetic resonance (NMR), and high pressure mercury intrusion (HPMI) tests) and multiple well-log datasets are integrated to unravel the variations of reservoir properties in different structural belts, and clarify the formation mechanisms of the fracture-pore-throat systems. The results show the Zhongqiu 1 gas field in the Qiulitage structural belt has the highest matrix porosity, and intergranular pores are preserved, while fractures are rare. The Keshen and Bozi-Dabei gas fields in the Kelasu structural belt contain large amounts of fractures, however, the matrix porosity is low, and the pore systems include intergranular pores and dissolution pores. Pore throat sizes in the Keshen gas field are tiny, and are narrow in the Bozi-Dabei gas field, then they become relatively wide in the Zhongqiu 1 gas field. Paleo stress controls formation of natural fractures, while in situ stress determines reservoir quality. The paleo stress in the Kelasu structural belt is much higher than the Qiulitage structural belt, and sandstones in the Keshen and Bozi-Dabei gas fields are more heavily fractured, while fractures in the Zhongqiu 1 gas field are rare. Stress will also drive sediment compaction and porosity reduction. Formation of fractures implies the release of paleo stress, and the in situ stress in Zhongqiu 1 gas field is high due to rareness of natural fractures. Low in situ stress intensity commonly implies low compactional porosity loss, and is favorable for porosity preservation. Intergranular pores can be preserved in the medium to coarse grained and well sorted sandstones, while poorly sorted or fine-grained sandstones are more tightly compacted. Fractures in the Keshen and Bozi-Dabei gas fields promote carbonate cementation. High quality intervals are those medium to coarse grained, well sorted sandstones with low in situ stress magnitude, where intergranular pores are well preserved, and they can constitute a favorable fracture-pore-throat network providing fractures are formed. The results unravel the variations of reservoir properties and clarify formation mechanisms of the Bashijiqike sandstones in different structural belts of Kuqa Depression, and have implications for reservoir quality prediction of deep and ultra-deep sandstones in similar basins worldwide.

1. Introduction

In sedimentary basins, reservoir properties are highly variable due to a range of structural elements (fracture and stress), depositional factors

(composition and texture) and variable diagenetic alterations (Morad et al., 2010; Higgs et al., 2017; Lai et al., 2018a). Especially in deep and ultra-deep strata, cementation and compaction will progressively reduce primary porosity, while dissolution and fractures will enhance porosity

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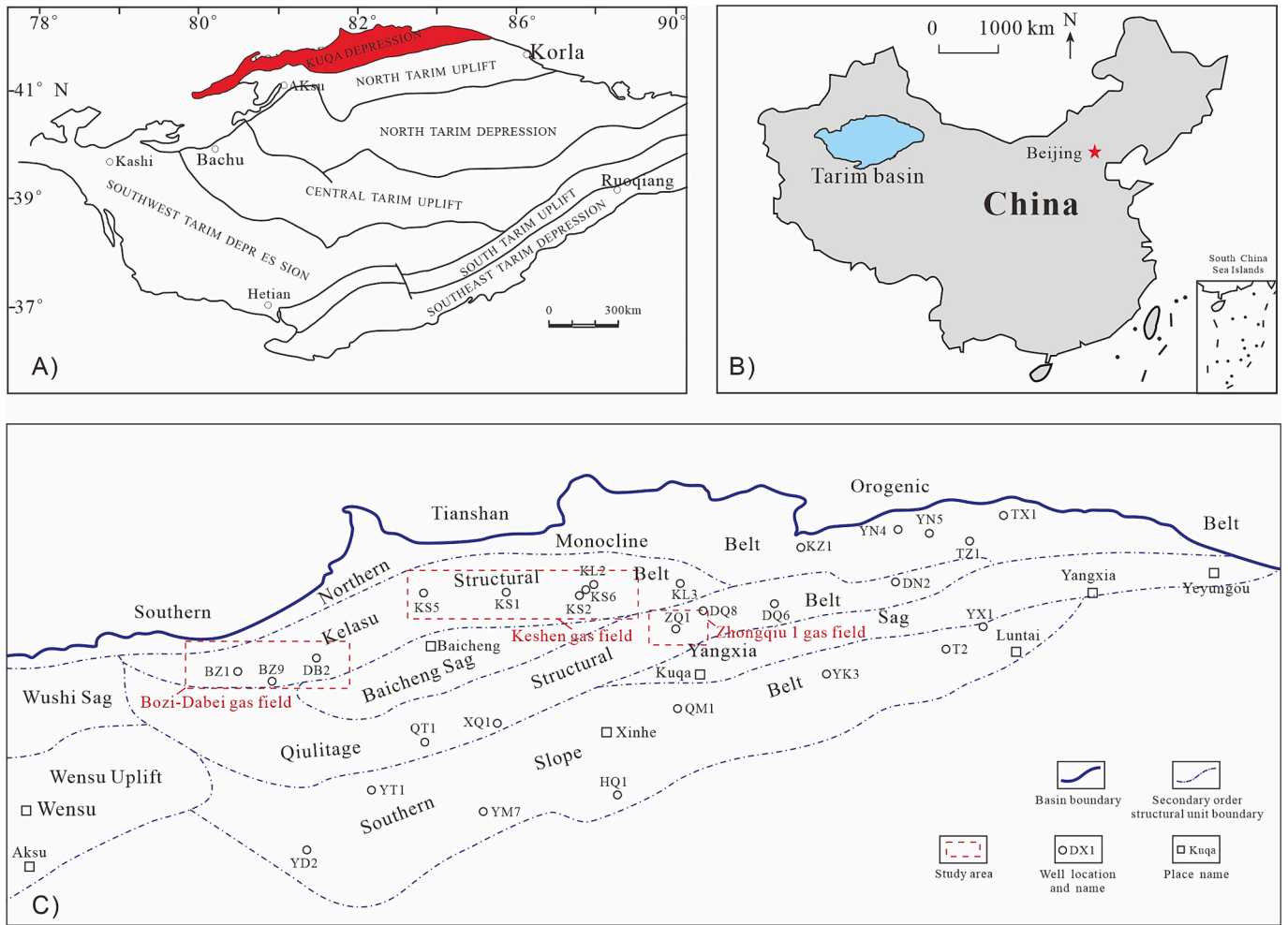


Fig. 1. Map showing structural divisions of Kuqa Depression (C) within North Tarim Basin (A), West China (B) (Jin et al., 2008; Lai et al., 2017a; Xu et al., 2022).

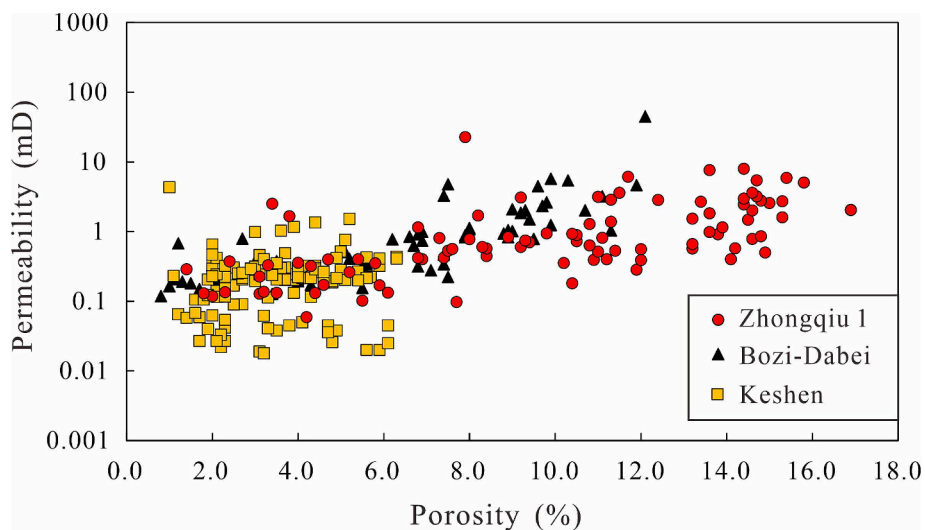


Fig. 2. Crossplot of permeability versus porosity of Cretaceous Bashijiqlike Formation for various structural belts in Kuqa Depression.

(Bloch et al., 2002; Worden et al., 2012; Freiburg et al., 2016; Hansen et al., 2017; Obradors-Prats et al., 2019). Oil and gas exploration is now shifting its focus towards deep and ultra-deep reservoirs, and reservoir properties are one of the greatest hydrocarbon exploration risks in deep and ultra-deep sandstones (Wilkinson and Haszeldine, 2011; Sathar and

Jones, 2016; Lai et al., 2017a; Wang et al., 2019; Løvstad et al., 2022). Understanding the spatial variability of reservoir properties and related formation mechanisms will significantly reduce uncertainties in reservoir characterization and hydrocarbon exploration in deep and ultra-deep sandstones (Freiburg et al., 2016; Becker et al., 2017; Li et al.,

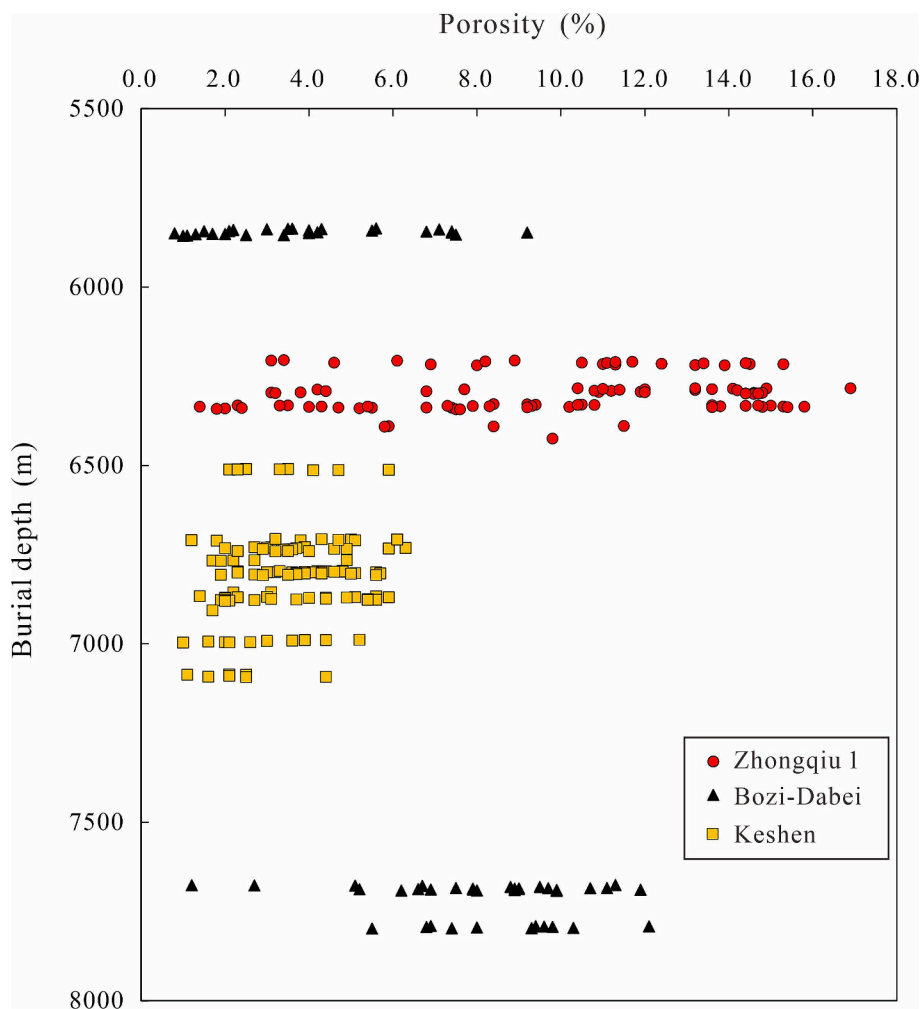


Fig. 3. Crossplot of porosity versus burial depth of Cretaceous Bashijiqi Formation for various structural belts in Kuqa Depression.

2023).

Though deeply and ultra-deeply buried, high industrial gas flows have been produced in the Bashijiqi Formation sandstones in the Kelasu and Qiulitage structural belts of Kuqa Depression (Guo et al., 2016; Lai et al., 2023a; Li et al., 2020; Su et al., 2024). Reservoir properties including the fracture-pore-throat systems show wide variations in the different structural belts, and different types of complex fracture-pore-throat systems in the Kuqa Depression can all deliver high hydrocarbon production (Lai et al., 2017a; Xin et al., 2022; Xu et al., 2022; Su et al., 2024). Up to now, no systematic studies have been performed on comparisons of reservoir properties in various structural belts of Kuqa Depression, and the fracture-pore-throat systems are poorly depicted from the comprehensive views of core, image logs and laboratory tests. In addition, little is known about the formation mechanisms causing the large variations in reservoir properties in the different structural belts. Depositional composition and texture determine the amounts of primary porosity (Bjørlykke, 2014; Xia et al., 2020; Li et al., 2023), and subsequent diagenetic modifications (compaction, cementation and dissolution) control the reduction of primary porosity and creation of secondary porosity (Morad et al., 2010; Bjørlykke and Jahren, 2012), while fracture improves reservoir permeability and tectonic stress has additional porosity reduction effects (Lai et al., 2019; Zeng et al., 2023; Laubach et al., 2023).

The main goals of this study are to unravel the variations of reservoir properties of the Bashijiqi sandstones in the Kelasu structural belt (Keshen gas field and Bozi-Dabei gas field) and Qiulitage structural belt (Zhongqiu 1 gas field) of Kuqa Depression, and to clarify the formation

mechanisms of the fracture-pore-throat systems in the different structural belts. The combinations of cores, thin sections, SEM, HPMI, and NMR tests are performed to characterize the fracture-pore-throat systems in the deep and ultra-deep sandstones of various structural belts in Kuqa Depression. Image logs are integrated to describe the subsurface fractures. Lastly, formation mechanisms of variations of fracture-pore-throat systems in different structural belts are clarified by integrating depositional, diagenetic and structural factors. The novelty of this study lies in the comparisons of reservoir properties of different structural belts of Kuqa Depression, and clarifying the formation mechanisms of complex fracture-pore-throat systems from the aspects of deposition, diagenesis and tectonic stress. The research results are hoped to provide insights into reservoir quality evaluation and hydrocarbon exploration of deep and ultra-deep sandstones in similar basins worldwide.

2. Geological settings

The Kuqa Depression is a foreland basin formed during the Mesozoic to Cenozoic orogenic events, and is very rich in natural gas resources (Zou et al., 2006; Dai et al., 2008; Jin et al., 2008; Lai et al., 2017a). Many giant gas fields have been discovered in the Kuqa Depression, including the Keshen-Kela and Bozi-Dabei gas field with reserves over $10,000 \times 10^8 \text{ m}^3$ in the Kelasu structural belt, and the Zhongqiu 1 gas field with reserves over $1000 \times 10^8 \text{ m}^3$ in the Qiulitage structural belt (Fig. 1) (Jin et al., 2008; Lai et al., 2017a; Xu et al., 2022; Zhao et al., 2025). The gas producing layers are mainly the Cretaceous Bashijiqi Formation (Su et al., 2024). The Bashijiqi Formation is deposited in a



Fig. 4. Core and thin section photos showing the fracture and pore spaces of Cretaceous Bashijiqi Formation of various structural belts in Kuqa Depression. A. Vertical partly-full cemented fracture, Keshen gas field, Keshen 601, 6156.1 m. B. Vertical partly-full cemented fracture, Keshen gas field, Keshen 601, 6155.76 m. C. Intergranular and intragranular pore spaces, Keshen gas field, Keshen 242, 6564.1 m. D. Network fractures, Bozi-Dabei gas field, Dabei 12, 5399.35 m. E. High dip angle fractures, Bozi-Dabei gas field, Bozi 301, 5840.8 m. F. Intergranular pore preserved, Bozi-Dabei gas field, Bozi 301, 5843.8 m. G. No fracture in fine-medium grained sandstone, Zhongqiu gas field, Zhongqiu 102, 6214.52 m. H. No fracture in fine-medium grained sandstone, Zhongqiu gas field, Zhongqiu 101, 6286.91 m. I. Abundant intergranular pores preserved, Zhongqiu gas field, Zhongqiu 101, 6283.35 m.

fan- braided deltaic environment, and the fine-medium grained sandstones act as reservoir rocks for these giant gas pools (Jia and Li, 2008; Wang et al., 2013). The Bashijiqi Formation is deeply to ultra-deeply buried and reservoir properties in different structural belts in the Kuqa Depression are greatly varied due to the complex geological activities including tectonic and diagenetic modifications (Lai et al., 2017a; Su et al., 2024; Li et al., 2025).

Fault-related folds formed during the orogenic events provide favorable traps for hydrocarbon accumulation in the Kuqa Depression (Zeng et al., 2010; Lai et al., 2017a). The Upper Triassic to Lower-Middle Jurassic lacustrine mudstones and coal seams are source rocks for hydrocarbon generation (Jin et al., 2008; Jia and Li, 2008). The widely distributed overlying Eocene Kumugeliemu Formation gypsum bearing mudstones are regional seals for gas accumulation (Xu et al., 2004; Zeng

et al., 2010). To conclude, the source rock-reservoir-seal assemblage provides favorable conditions for the formation of giant gas pools in the Kuqa Depression.

High industrial gas flows have been produced in the Bashijiqi Formation sandstones. Though deeply and ultra-deeply buried of the Bashijiqi sandstones, a wide range of fracture-pore-throat systems are formed due to complex structural and diagenetic modifications (Lai et al., 2022a), and they make significant contributions for formation of effective reservoirs as well as the high hydrocarbon productivities. The drilled core data, well log data and gas production data prove that the reservoir properties in terms of fracture-pore-throat systems are widely varied in various structural belts (Kelasu structural and Qiulitage structural belts, etc) of Kuqa Depression (Lai et al., 2022a, 2023a; Su et al., 2024).

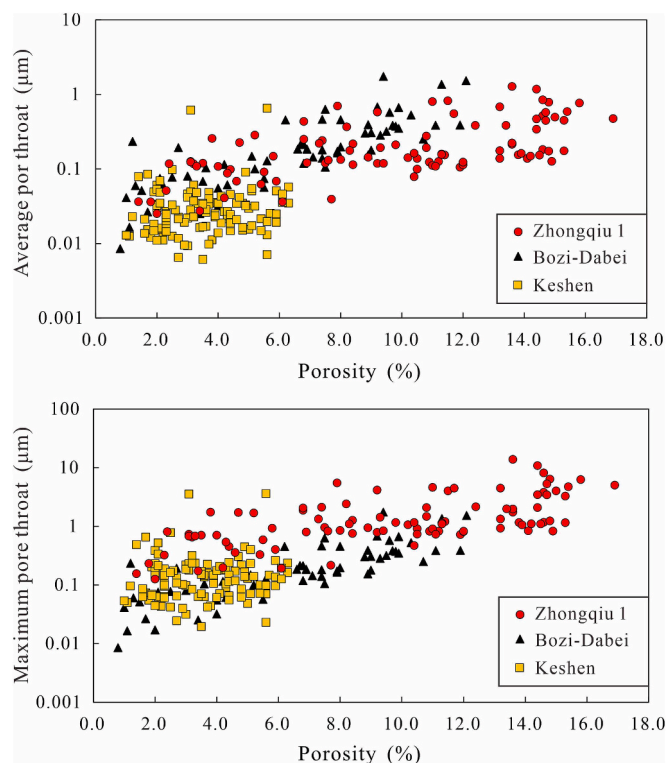


Fig. 5. Crossplot of average pore throat size and maximum pore throat sizes versus porosity of Cretaceous Bashijiqike Formation for various structural belts in Kuqa Depression.

3. Samples and analytical methods

Large amounts of core data are taken from the various structural belts in the Kuqa Depression. Cores, which are taken from the recently drilled wells, are 360° scanned to capture the lithology, sedimentary structures as well as presence of fractures. Core plug samples (2.5 cm diameter and about 5 cm in length cylinders) are taken from the whole-diameter core, and are prepared for porosity and permeability tests, then for NMR measurements, and lastly the HPMI tests. Additionally, thin section, SEM, and CT scanning analysis are used to understand the fracture-pore-throat systems.

The storage (porosity) and flow (permeability) capacity of the reservoir are obtained by routine rock properties measurements performed on the core plug samples.

Then thin section analysis is performed to highlight the pore spaces by impregnated with blue epifluorescent epoxy. Thin section images are taken at the plane-polarized light and cross-polarized light. Also thin sections are stained with Alizarin red S and K-ferricyanide for identification of carbonates (calcite, ferroan calcite, and ferroan dolomite). Point-count analysis was performed with respect to detrital framework grains, matrix and cement.

Scanning electron microscopy (SEM) analysis is conducted on the freshly broken and gold coated rocks at the national key laboratory of petroleum resources and engineering, with the aim to identify the microscopic pore-throat systems as well as the various types of clay minerals. The regular SEM photomicrographs are secondary electron images.

Core plug samples are also scanned using a μ CT (micro-CT) instrument, and the two-dimensional (2D) grayscale images as well as three-dimensional (3D) reconstructed images provide insights into the fracture-pore-throat systems.

Core plug samples are fully (100%) saturated and unsaturated (centrifuged), and nuclear magnetic resonance (NMR) measurements are performed respectively to obtain the incremental and cumulative

transversal relaxation time (T_2) spectra at saturated and centrifuged status. The echo spacing is set as 0.2 mS, and the waiting time is 6 S.

High pressure mercury intrusion (HPMI) measurement is always lastly conducted since it will destroy rock samples, and capillary pressure curves as well as related threshold pressure (P_d), medium pore throat radius (r_{50}) and maximum pore radius (r_{max}) can be obtained. A mercury porosimeter with maximum injection pressure of 180.29 MPa is used, pore throat systems $> 0.0042 \mu\text{m}$ can be invaded by mercury, and then the volume of mercury entered into the pore bodies will be measured. Then the mercury will extrude with the mercury pressure gradually decreased.

Geophysical well logs will help interpret the lithology, detect sub-surface fractures and evaluate stress. Conventional log suite including natural gamma-ray (GR), sonic transit time (AC), bulk density (DEN), compensated neutron (CNL), resistivity logs (including high-definition resistivity log), as well as image logs, sonic scanner logs are utilized to better understand the reservoir property variations.

4. Results

4.1. Reservoir property variations

From the core test data (depth ranges from 5835.58 to 7797.94 m), the deep and ultra-deep Bashijiqike sandstones in the Kuqa Depression show a wide range of porosity and permeability, and wide variations are observed in different gas fields (Fig. 2). The Zhongqiu 1 gas field has the highest matrix porosity and permeability, while the matrix reservoir quality of Keshen gas field is lowest (Fig. 2). The presence of fractures may significantly enhance permeability, however, core plugs used for routine core analysis commonly contain no evident fractures, and permeability shows an evident increasing trend with porosity (Fig. 2).

As is shown in Fig. 3, porosity in various structural belts shows different trends with burial depth (Fig. 3). Though buried to a great depth at about 8000 m in the Bozi-Dabei gas field, the Bashijiqike sandstones can still keep a porosity as high as 10.0%. Furthermore, the fine to medium grained sandstones in the Zhongqiu 1 gas field are buried to 6200 to 6400 m depths, but porosity is preserved as high as 16.0% (Fig. 3). The porosity–depth plot does not reveal a normal decrease of porosity with increasing burial depth (Fig. 3).

4.2. Variation of fracture-pore-throat systems

Fracture appearances are varied significantly in the different gas fields of Kuqa Depression (Su et al., 2026). Core observation reveals that the Bashijiqike sandstones in the Keshen and Bozi-Dabei gas fields are heavily fractured (Fig. 4). Vertical fractures, high angle and low angle are commonly detected, and some of the fracture planes are partly to fully filled by calcite cements (Fig. 4A, B, E, F). In some cases, network fractures with various dip angles can be observed (Fig. 4E). In contrast, no evident fractures can be detected in the Bashijiqike sandstones of Zhongqiu 1 gas field (Fig. 4G, H).

Microscopic thin section analysis proves the pore spaces are also different in the Keshen, Bozi-Dabei and Zhongqiu 1 gas fields (Fig. 4C, F, I). Fine to medium grained sandstones in the Keshen gas field contain mainly intergranular and intragranular pores (Fig. 4C), while the sandstones in the Bozi-Dabei gas field are dominantly of residual intergranular pore spaces and minor amounts of dissolution pores (Fig. 4F). The high matrix porosity of sandstones in the Zhongqiu 1 gas field is mainly the contribution of intergranular pores. As can be observed in Fig. 4I, many intergranular pores are preserved, and connectivity of pore throat systems is good.

Therefore, the maximum pore throat size (r_{max}) for the Bashijiqike sandstones in Keshen gas field is in a narrow range from 0.02 to 3.62 μm , and also the average pore throat size (r_{ave}) is only in the range from 0.006 to 0.65 μm (Fig. 5). Thin section and SEM images prove the pore spaces are mainly dissolution pores and micropores associated with clay

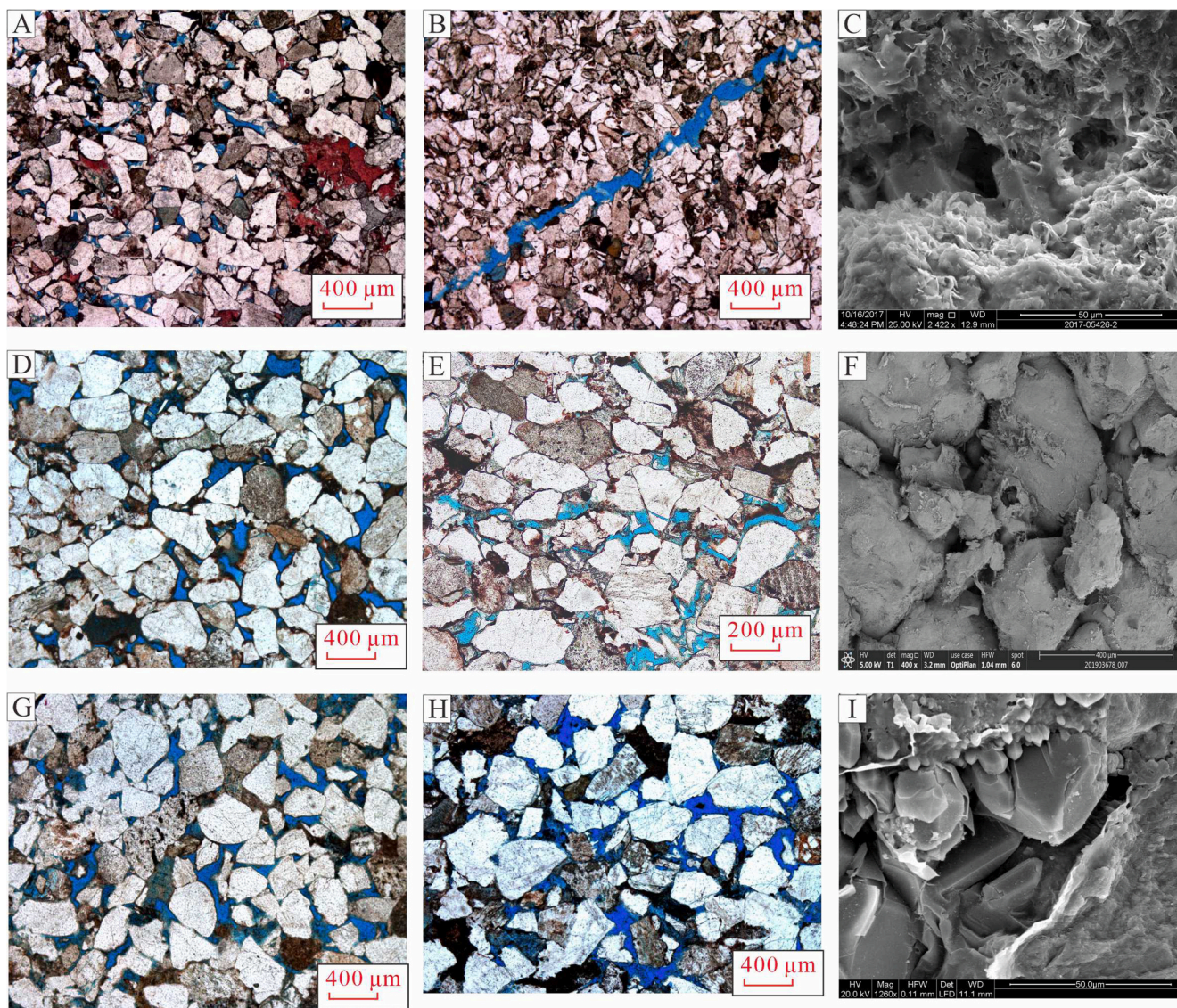


Fig. 6. Thin section and SEM images showing the pore throat structure of Bashijiqi sandstones in various structural belts in Kuqa Depression. A. Keshen 242, 6562.8 m; B. Keshen 242, 6568.95 m; C. Keshen 242, 6440.45 m. D. Bozi 9, 7689.91 m; E. Bozi 104, 6802.14 m; F. Bozi 9, G. Zhongqiu 101, 6283.09 m; H. Dongqiu 5, 4940.63 m; I. Zhongqiu 101, 6283.09 m.

minerals (Fig. 6A, C). The matrix pore throats (dissolution pore and tiny throat) show poor connectivity, however, microfractures are commonly detected (Fig. 6B).

The r_{\max} ranges from 0.04 to 8.79 μm for the Bashijiqi sandstones in Bozi-Dabei gas field, and the r_{ave} is in the range from 0.01 to 1.74 μm (Fig. 5). Thin section and SEM images reveal the presence of intergranular pores and minor amounts of dissolution pores (Fig. 6D, 6F), and the presence of microfractures is also evidenced by thin sections (Fig. 6E). The matrix pore throat (intergranular pore and narrow throat) shows a moderate poor connectivity.

The Bashijiqi sandstones in the Zhongqiu 1 gas field have the highest pore throat size. The r_{\max} has a wide range from 0.13 to 13.85 μm for the Bashijiqi sandstones in Zhongqiu 1 gas field, and the r_{ave} is in the range from 0.03 to 1.28 μm (Fig. 5). Even containing no microfractures, the abundance of intergranular pores and relatively wider pore throats contributes to a relatively good pore throat connectivity (Fig. 6G, H, I).

The HPMI curves and NMR T_2 spectra are used to unravel the differences of pore-throat systems in various gas fields. Under the injection pressure of 180.29 MPa, most rock samples have a maximum mercury

saturation higher than 80%, implying most pores are connected by throats (Fig. 7). From the capillary curve shapes and capillary parameters, the Zhongqiu 1 gas field has the best pore-throat connectivity (Fig. 7E), while the Keshen gas field has the poorest pore-throat connectivity (Fig. 7A). Intergranular pores in the Bozi gas field are also connected by effective pore throats (Fig. 7C). The mercury withdrawal curve indicates most of the mercury (>60%) is residual in the rocks, and even in Zhongqiu 1 gas fields, only 15% of the mercury is extruded after the mercury pressure gradually decreased (Fig. 7).

The NMR T_2 spectra of the different gas fields are also greatly varied, and the T_2 magnitudes and NMR porosity in Keshen gas field are lowest, while the Zhongqiu 1 gas field has the highest T_2 magnitudes and NMR porosity (Fig. 7B, F). In addition, most of the pores in Zhongqiu 1 gas field are mobile, and the residual water saturation is less than 30% (Fig. 7F). Sandstones in Keshen gas field have only about 6.0% NMR porosity, and the capillary and clay-bound water content reaches as much as 4.0%, indicating more than 60% are immobile (Fig. 7B). Also the sandstones in the Bozi-Dabei gas field also have a high residual water content (>50%) (Fig. 7D).

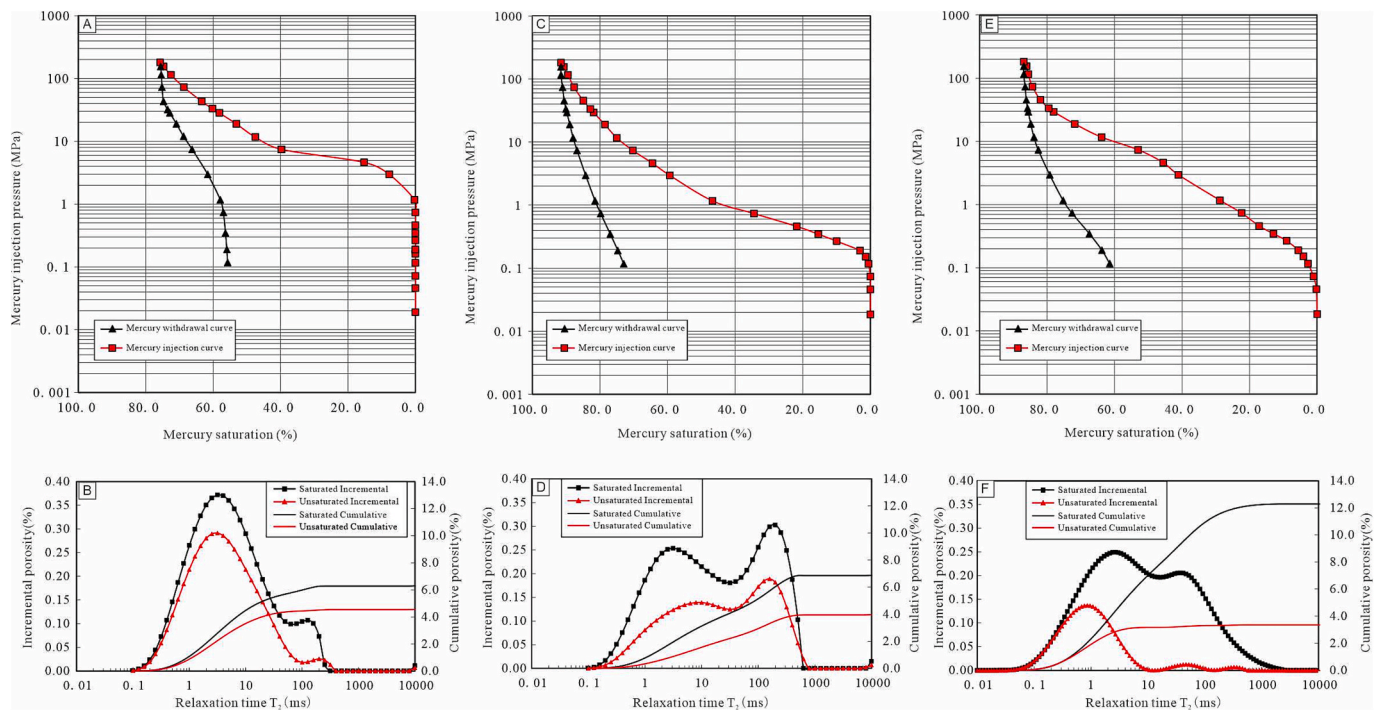


Fig. 7. Capillary curves and NMR T_2 spectrum showing the pore throat structure of Bashijiqike sandstones in various structural belts in Kuqa Depression. A. Keshen 241, 6562.8 m; B. Keshen 13, 7340.23 m. C. Bozi 9, 7689.91 m; D. Bozi 104, 6842. 20 m. E. Zhongqiu 101, 6283.09 m; F. Zhongqiu 102, 6217.04 m.

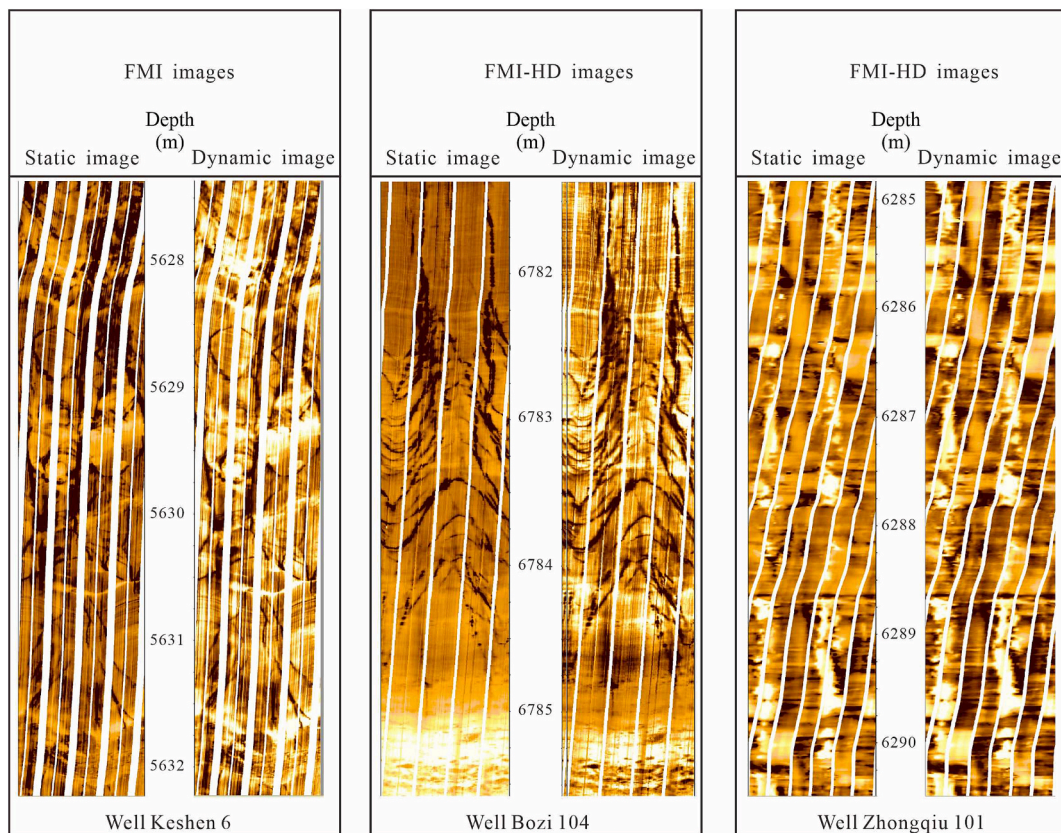


Fig. 8. Image logs showing fracture appearances of Bashijiqike sandstones in various structural belts in Kuqa Depression.

4.3. Fracture-pore-throat systems and hydrocarbon productivity

Hydrocarbon productivity is mainly controlled by the combination

of fracture-pore-throat systems (Lai et al., 2020). Both matrix pore throats and fractures determine the hydrocarbon productivity under the certain choke width and drawdown pressure. Presence of fracture

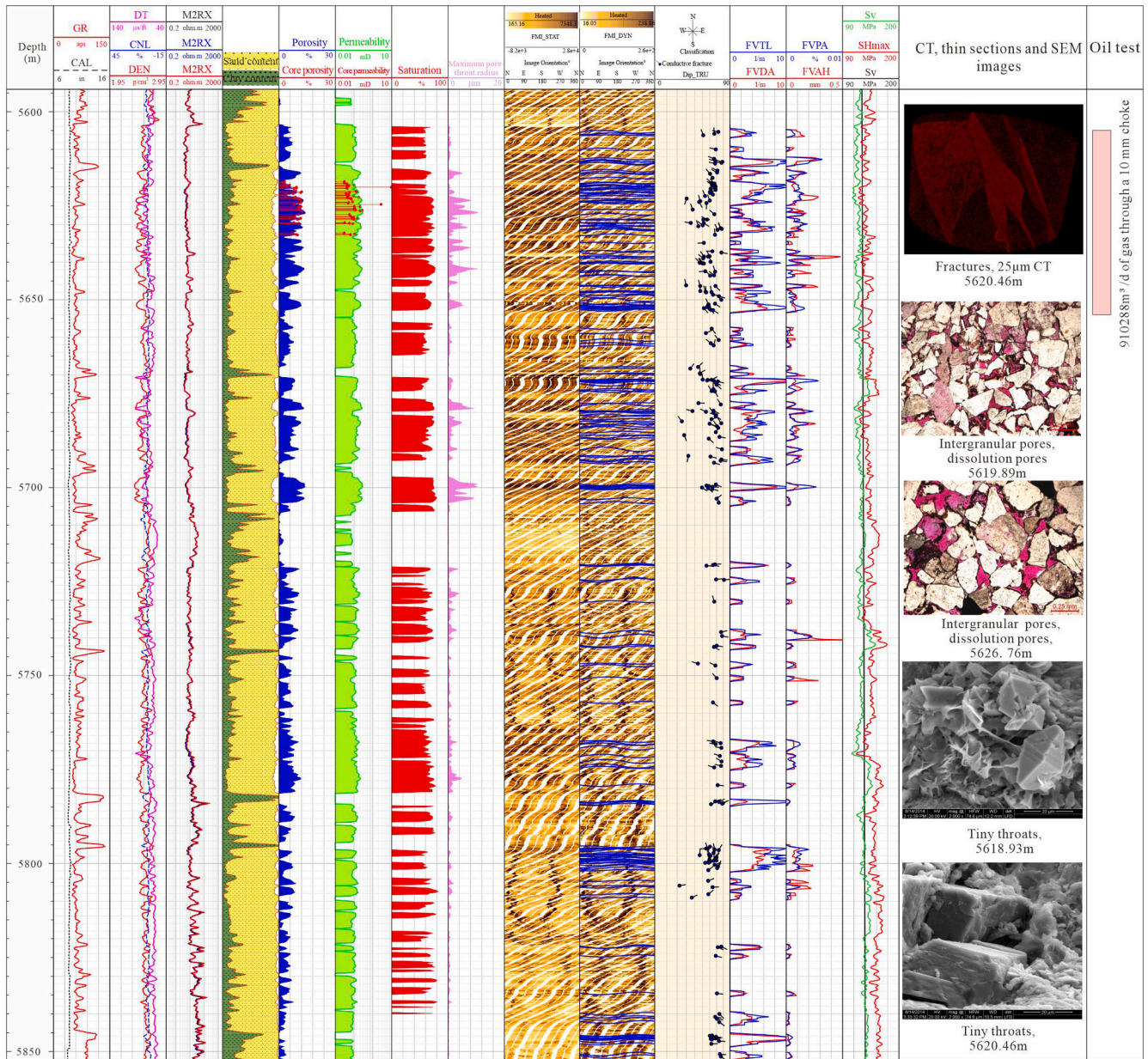


Fig. 9. Fracture-pore-throat assemblage and hydrocarbon productivity of Well Keshen 6 in Kelasu structural belt in Kuqa Depression.

determines the high daily oil and gas production, while the matrix pore throat systems control the cumulative oil and gas production (Zou et al., 2012; Lai et al., 2023a; Han et al., 2023; Su et al., 2024).

Low porosity or tight reservoirs with abundant natural fractures can still contribute to a very high hydrocarbon productivity since natural fractures play as important fluid flow channels during production (Lai et al., 2017b). On the contrary, reservoirs containing no evident natural fractures can also keep a high daily especially cumulative hydrocarbon productivity providing that a good pore throat connectivity of reservoirs (Lai et al., 2018b). Therefore, various combination of fracture-pore-throat systems will have varied hydrocarbon productivity.

Fracture-pore-throat systems are significantly varied in the different gas fields in the Kuqa Depression, however, no matter the Keshen gas field, or Bozi-Dabei gas field, or even the Zhongqiu 1 gas field, high industrial hydrocarbon productivities have been obtained. In the year 2008, the Well Keshen 2 in the Kelasu structural belt has obtained a daily gas production of 459528 m³ in the 6573–6609 m and 6640–6697 m intervals (6 mm choke, drawdown pressure of 70.88 MPa. In the year

2018, the Zhongqiu 1 Well in the Zhongqiu 1 gas field obtained a daily gas production of 33.4 × 10⁴ m³ and daily oil production of 21.4 m³ in 6073–6182 m intervals. In the year 2019, the Bozi 9 in the Bozi-Dabei gas field has obtained a daily gas production of 705498 m³ and daily oil production of 167 m³ in 7677–7760.5 m intervals (8 mm choke, drawdown pressure of 94.4 MPa).

Hydrocarbon productivity is closely associated with the fracture-pore-throat systems (Su et al., 2024). Image logs help recognize and detect subsurface fractures, and calculate fracture porosity and fracture density (Lai et al., 2018c, 2023b; Su et al., 2024).

Image logs reveal that the sandstones in the Keshen and Bozi-Dabei gas fields contain a large number of fractures, while in the Zhongqiu 1 gas field, absolutely no fractures can be detected (Fig. 8).

The Well Keshen 6 in the Keshen gas field, has obtained a daily natural gas production of 740000 m³ in the depth intervals (Fig. 9). The matrix porosity is mainly 6.0% to 10.0%, and the r_{max} can reach as high as 5 µm. In addition, sandstones in the gas test intervals are heavily fractured, and the fracture porosity can reach at about 0.5%, and the

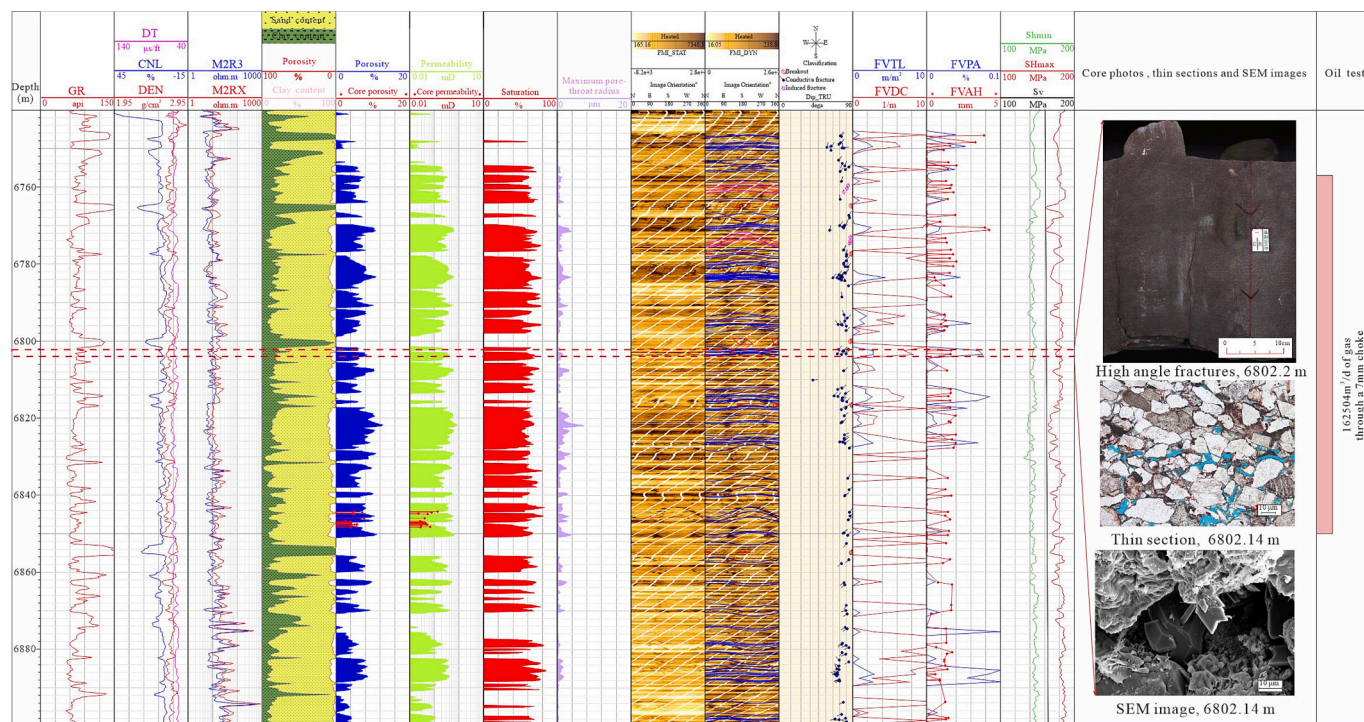


Fig. 10. Fracture-pore-throat assemblage and hydrocarbon productivity of Well Bozi 104 in Kelasu structural belt in Kuqa Depression.

fracture density can reach as high as 10 numbers per meter (Fig. 9).

The Well Bozi 104 in the Bozi-Dabei gas field has obtained a daily natural gas production of 162504 m³ in the 6757–6850 m depth intervals (Fig. 10). Also the matrix porosity is mainly 8.0% to 12.0%, and the r_{max} can be more than 10 μm. Additionally, sandstones in the Well Bozi 104 are also heavily fractured, and the fracture porosity can reach at about 0.5%, and the fracture density can reach as high as 10 numbers per meter (Fig. 10).

The Well Zhongqiu 101 in the Zhongqiu 1 gas field has obtained a daily gas production of 90781 m³ and a daily water production of 74.80 m³ in the intervals 6270.5–6290.5 m (Fig. 11). The fracture-pore-throat system analysis indicates that no fractures are observed, but the matrix porosity can reach as high as 12.0% to 16.0%, and the r_{max} can be more than 12 μm (Fig. 11). Thin sections prove the favorable pore throat connectivity in the Well Zhongqiu 101 (Fig. 11).

5. Discussion

The three gas fields in the Kelasu and Qiulitage structural belts have varied fracture-pore-throat systems, and high industrial hydrocarbon flows have been obtained from the different fracture-pore-throat assemblages. The Zhongqiu 1 gas field in the Qiulitage structural belt has the highest matrix porosity, and the abundant intergranular pores together with the wide pore throats can maintain a high hydrocarbon productivity even without the contribution of natural fractures. In contrast, the matrix porosity of Keshen gas field in the Kelasu structural belt is lowest, and the pore-throats are dominantly of intergranular and intragranular dissolution pores. Though with low matrix porosity and narrow pore throats, the high fracture density will make a great contribution to hydrocarbon productivity in the Keshen gas field. In addition, in the Bozi-Dabei gas field in the Kelasu structural belt, the fracture-pore-throat systems are dominantly of residual intergranular pores and fractures, a good connectivity between fracture and pore-throats will also result in a high hydrocarbon productivity.

The wide variations of fracture-pore-throat systems and reservoir quality in the various gas fields in Kuqa Depression are attributed to the complex combination of structural, depositional and diagenetic factors

(Lai and Wang, 2015).

Reservoir quality and the fracture-pore-throat systems are the comprehensive reflections of initial depositional composition and texture (Bjørlykke, 2014), and subsequent diagenetic modifications (Morad et al., 2010; Bjørlykke and Jahren, 2012; Lai et al., 2016), as well as structural factors including fracture (Laubach et al., 2023) and the tectonic stress (Lai et al., 2019).

Depositional facies control initial sediment composition and texture, and determine the primary porosity and subsequent diagenetic behaviors during progressive burial (Bjørlykke, 2014). Diagenetic modifications are key factors controlling matrix porosity through compaction, cementation and dissolution of framework grains (Morad et al., 2010). Structural factors on the one hand will result in the formation of natural fractures, and will improve reservoir quality and hydrocarbon productivity (Zeng, 2010; Lyu et al., 2016, 2017; Laubach et al., 2019; Su et al., 2026). On the other hand, tectonic stress also plays an important role in controlling reservoir quality, and intensive stress may have additional porosity reduction effects through stress driven compaction (Lai et al., 2022a).

5.1. Structural factors

Tectonic stress controls the formation of natural fractures, and the additional porosity reduction by stress. Stress fields mainly include paleo stress and in situ stress, and paleo stress refers to the ancient tectonic stress rocks experienced in the geological histories, while the in situ stress is the still active tectonic stress (Yang and Wang, 2023).

High paleo stress will gradually reduce the intergranular pores through tectonic compaction, and then natural fractures will be formed if the paleo stress exceeds the rock strength (Zhang et al., 2021; Wei et al., 2022). Then the intensive stress will be released due to formation of natural fractures, and then the stress relief will be favorable for porosity preservation.

5.1.1. Paleo stress and fracture formation

Paleo stress is an important factor determining reservoir properties (Zeng et al., 2010; Wei et al., 2022). On the one hand, the paleo stress

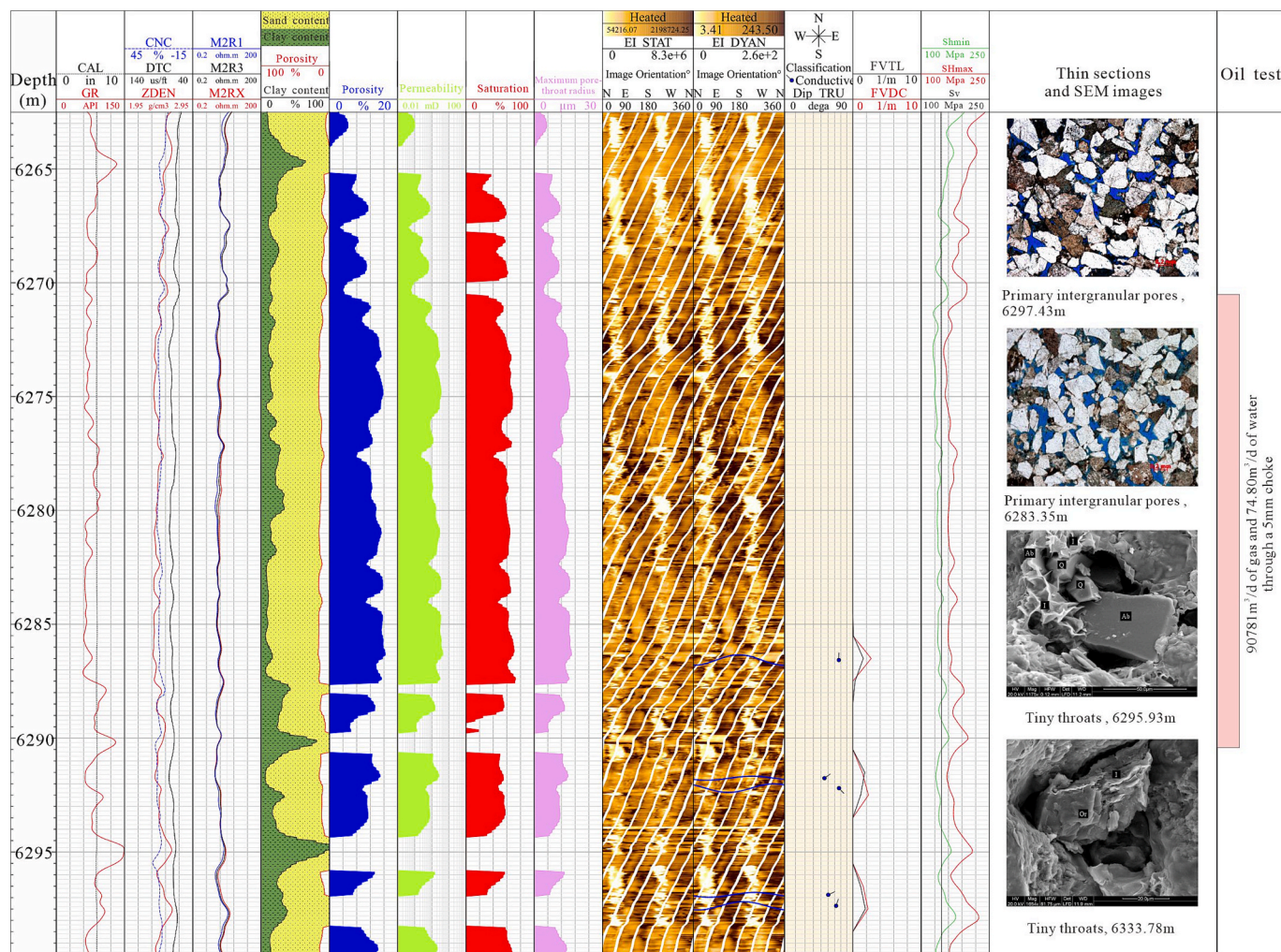


Fig. 11. Pore-throat assemblage and hydrocarbon productivity of Well Zhongqiu 101 in Qiulitage structural belt in Kuqa Depression.

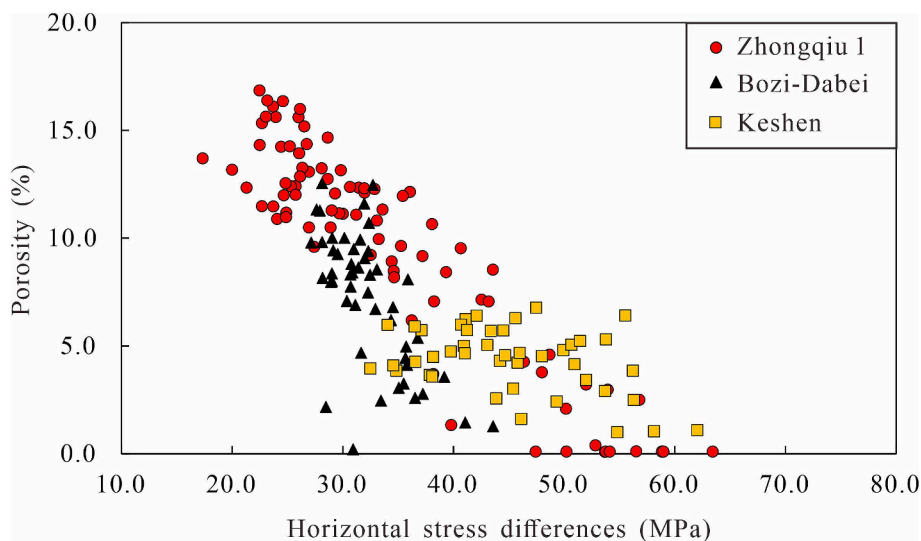


Fig. 12. Crossplot of porosity versus horizontal stress differences of Cretaceous Bashijiqlike Formation for various structural belts in Kuqa Depression.

magnitude will result in porosity loss, and porosity reduction due to tectonic compaction by paleo stress can reach 8.5% per 100 MPa (Zhang et al., 2011). On the other hand, paleo stress is the main driving forces for the formation of natural fractures, and intensive paleo stress

magnitude will result in a high density of fractures (Zhang et al., 2021; Wei et al., 2026).

Acoustic emission (AE) methods can reflect the stress activities rocks experienced (Lin et al., 2025; Wang et al., 2025). According to the

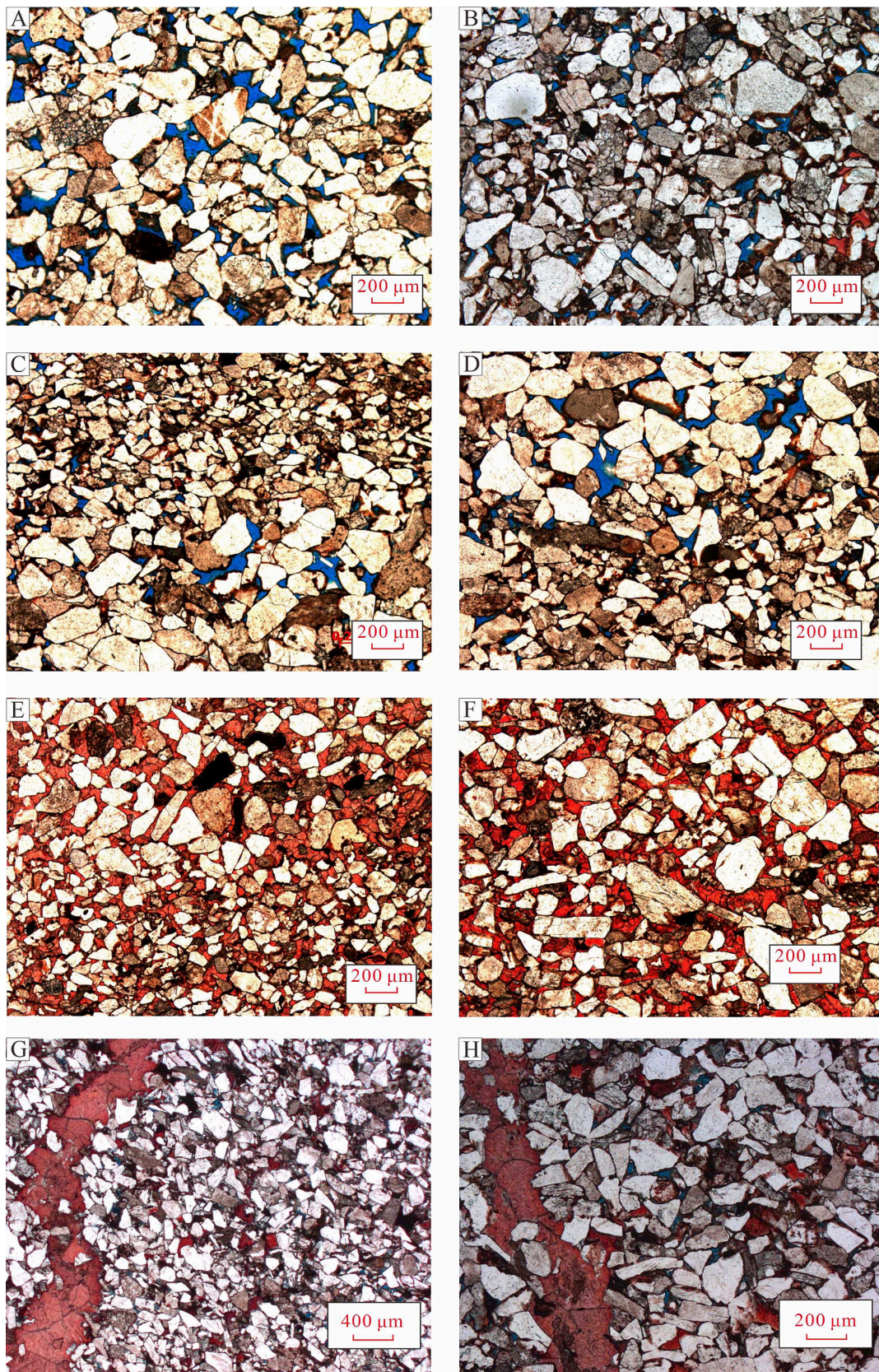


Fig. 13. Thin section showing the compaction and carbonate cements of Bashijiqi sandstones in Kuqa Depression. A. Intergranular pores in coarse-grain size and well sorted rocks, Bozi 9, 7675.7 m. B. Tightly compacted due to poor sorting, Bozi 9, 7688.25 m. C. Different compacted porosity loss due to varied grain size, Bozi 9, 7678.04 m. D. Intergranular pores preserved in coarse-grain size and well sorted rocks, while pores in fine-grained rocks are rare, Bozi 9, 7680.34 m. E. Abundant carbonate cements, Bozi 9, 7676.38 m. F. Abundant carbonate cements, Bozi 9, 7676.78 m. G. Carbonate cements along fracture planes, Bozi 22, 6323.64 m. H. Carbonate cements along fracture planes, Bozi 22, 6328.92 m.

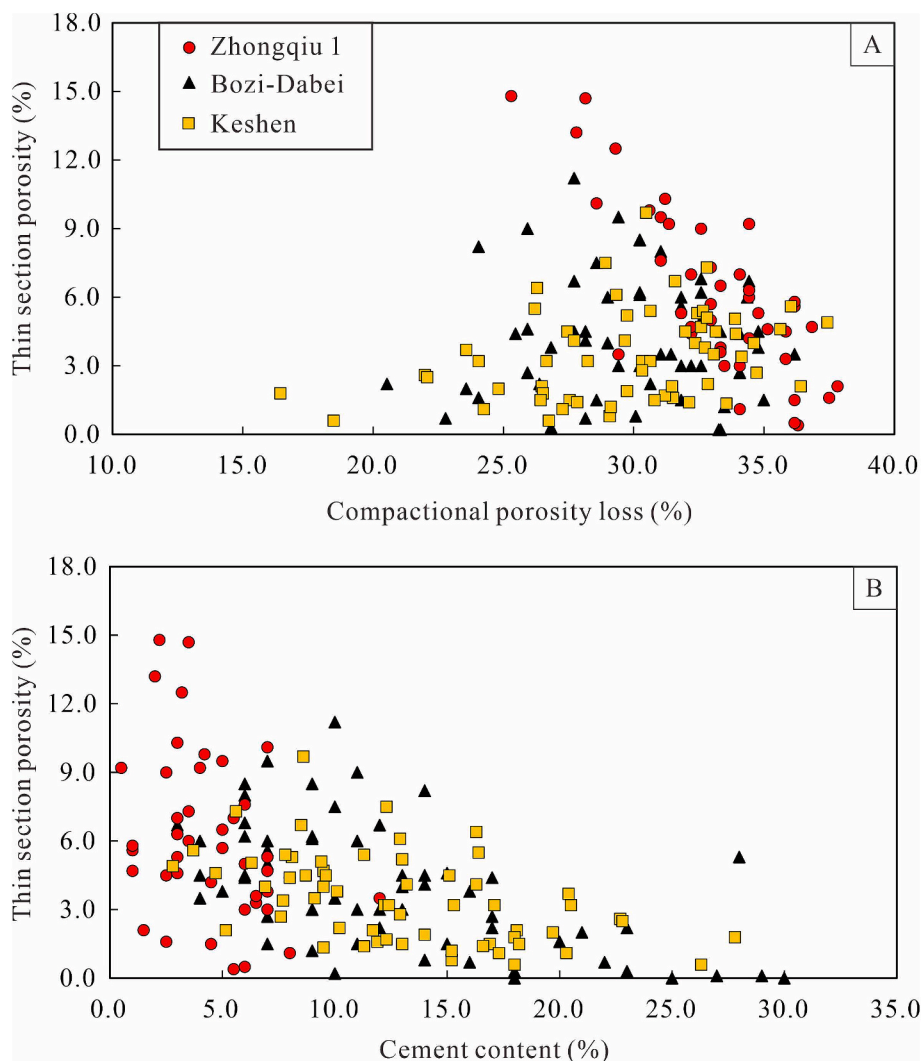


Fig. 14. Plots of thin section porosity versus compactional porosity loss and cement content of Bashijiqi sandstones in various structural belts in Kuqa Depression.

acoustic emission tests, the paleo stress reaches as high as 156.2 MPa (average 90–110 MPa) in the Kelasu structural belt (Keshen and Bozi-Dabei gas fields), and decreases quickly into 70–90 MPa in the Qiulitage structural belts (Zhongqiu 1 gas field) (Li et al., 2017; Zeng et al., 2020). Consequently, sandstones in the Keshen and Bozi-Dabei gas fields are heavily fractured due to high paleo stress, while fractures in the Zhongqiu 1 gas field are rare due to relatively low paleo stress.

Burial depth is an important factor controlling stress distribution. As can be seen from Fig. 3, the burial depth of the Bashijiqi Formation sandstones in the Zhongqiu 1 gas field (6200–6400 m) is significantly shallower than that in the gas fields of the Kelasu structural belt (up to 7800 m). Therefore the shallower burial depths in the Zhongqiu 1 gas field imply a low paleo stress magnitude, and a higher porosity than those of Keshen and Bozi-Dabei gas fields.

5.1.2. In situ stress and porosity reduction

In situ stress field is the inheritance and development of paleo stress field, and is the still active stress (Yang and Wang, 2023). Therefore, the in situ stress magnitude determines the matrix porosity and even fracture effectiveness (Feng et al., 2019; Lai et al., 2024; Li et al., 2025). Formation of natural fractures commonly implies the release of paleo stress, and also will result in a low in situ stress magnitude (Fan et al., 2021; Lai et al., 2025; Zhang et al., 2026). Consequently, the high paleo stress concentration is released by formation of fractures in the Keshen and Bozi-Dabei gas fields, and the in situ stress magnitudes will be low,

and intergranular pores can thus be preserved. The areas or intervals with a low stress are favorable for porosity preservation and hydrocarbon accumulation (Zeng et al., 2010; Lai et al., 2019).

Geophysical well logs can be used for the calculation of in situ stress magnitudes (vertical stress S_v , maximum horizontal stress S_{Hmax} , minimum horizontal stress S_{Hmin}) through combined spring model by calibrating with hydraulic fracturing tests (Radwan et al., 2021; Lai et al., 2022b; Roshan et al., 2023).

The horizontal stress difference ($\Delta\sigma = S_{Hmax} - S_{Hmin}$), which reflects the horizontal stress concentration, is an important factor controlling reservoir quality and even hydraulic fracturing design (Lai et al., 2019; Wang et al., 2021; Yong et al., 2022).

Previous studies reveal the paleo stress in the Kelasu structural belt is much higher than that in the Qiulitage structural belts (Li et al., 2017; Zeng et al., 2020). However, the calculated in situ stress magnitudes using well log data in the Kelasu structural belt are lower than the Qiulitage structural belts (Fig. 12), therefore, the large amounts of natural fractures formed in the Kelasu structural belt imply paleo-stress release (Li et al., 2017; Zeng et al., 2020; Zhang et al., 2021; Wei et al., 2022).

As is shown in Fig. 12, there is an evident decreasing trend with horizontal stress difference for all the three gas fields (Fig. 12). The horizontal stress differences are highest in the Zhongqiu 1 gas field since there is no release of stress by fracture formation, however, for those high quality intervals (porosity > 10%), $\Delta\sigma$ values are also low (Fig. 12).

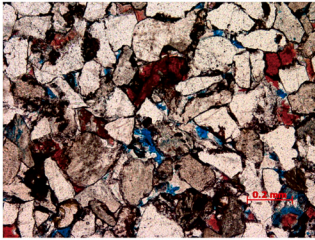
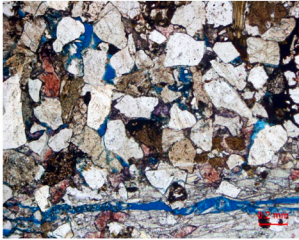
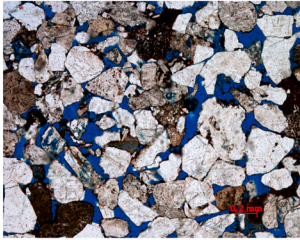
Gas fields of different structural belts		Keshen gas field	Bozi-Dabei gas field	Zhongqiu 1 gas field
Typical thin section images				
		Keshen 242, 6568.3 m	Dabei 902, 5095.9 m	Zhongqiu 101, 6298.19 m
Fracture-pore-throat systems		Many dissolution pores and minor intergranular pores, and abundant fractures	Coexistence of dissolution pores and intergranular pores, and many fractures	Large amounts of intergranular pores, and no evident fractures
Mechanisms for variations of fracture-pore-throat systems	Paleo stress	Reaches as high as 156.2 MPa, and averaged as 90-110 MPa	90-130 MPa	Only 70-90 MPa
	In situ stress	Averaged as 30-60 MPa	Averaged as 25-45 MPa	A wide range from 20-60 MPa
	Depositional factors	Fine to medium grained, and well sorted sandstones	Fine to medium grained, and well sorted sandstones	Fine to medium grained, and well sorted sandstones
	Diagenetic factors	Tightly compacted and abundant carbonate cements	Moderately compacted and many carbonate cements	Limited compaction and minor carbonate cements

Fig. 15. Schematic diagram showing the variations of fracture-pore-throat systems in different gas fields as well as the mechanisms from stress, depositional and diagenetic factors in the Kuqa Depression.

Relatively high porosity reservoirs are mostly associated with the low $\Delta\sigma$ layers (Fig. 12). The horizontal stress differences in the Keshen gas field are higher than those in the Bozi-Dabei gas field, and the matrix porosity is lowest due to very high paleo stress (Fig. 12).

The porosity loss by in situ stress can also be called “tectonic compaction”, which describes the stress driving sediment compaction and porosity reduction (Fan et al., 2021; Zhang et al., 2021).

5.2. Controls of composition and texture on reservoir properties

In the Kuqa Depression, rocks with evident intergranular pores and even dissolution pores are always those medium grained sandstones which are well sorted (Fig. 6D, G, H). Therefore the depositional composition and texture exert the primary roles in determining reservoir quality. Medium to coarse grained and well sorted sandstones tend to have more primary porosity, and have the ability preventing mechanical compaction (Salem et al., 2000) (Fig. 13A). Conversely, poorly sorted or fine to very fine grained sandstones are always tightly compacted due to the overburden stress and the additionally horizontal stress (Fig. 13B–D).

5.3. Diagenetic factors

Mechanical and chemical compaction significantly reduce depositional porosities during burial (Higgs et al., 2007; Dutton and Loucks, 2010; Bjørlykke, 2014; Sathar and Jones, 2016). Clay-rich or very fine-grained sandstones will be more compacted (Weber and Ricken, 2005; Sathar and Jones, 2016). Given the complexity of depositional composition and texture, the degree of compaction and compactional porosity

loss is variable due to the extensive stress (Tobin et al., 2010; Stricker et al., 2016).

Plot of thin section porosity versus compactional porosity loss shows an evident negative trend, and all the three gas fields have experienced extensive compaction (Fig. 14A). There are some samples displaying low thin section porosity even with low compactional porosity loss values, and these samples contain extensive carbonate cements. Therefore, cementation is another factor reducing porosity (Fig. 14B).

Different compacted porosity loss due to varied grain size can be observed even in a same thin section (Fig. 13C and D). Intergranular pores are commonly preserved in coarse-grain size and well sorted rocks, while pores in fine-grained rocks are rare (Fig. 13C and D). Consequently, sandstones with different composition and texture have varied compactional porosity loss in the same stress status (vertical stress and horizontal stress) (Fig. 13C and D).

Carbonate cements are common cementing materials in sandstones, and they exert strong controls on reservoir properties (Dutton, 2008; Loyd et al., 2012). Sandstones in all the three gas fields contain abundant carbonate cements, which significantly reduce the intergranular pores (Fig. 13E, F). Plot of thin section porosity versus cement content shows that the Bashijiqike sandstones are more cemented in the Keshen and Bozi-Dabei gas fields than in the Zhongqiu 1 gas field (Fig. 14B). As previously stated, fractures in the Kuqa Depression are commonly cemented by carbonate cements (Fig. 4A, B, D), and in addition thin sections can capture the cementation phenomenon along the fracture planes (Fig. 13G, H). Natural fractures in the Keshen and Bozi-Dabei gas fields tend to enhance fluid flow, and promote carbonate cementation along the fracture planes (Fig. 14B).

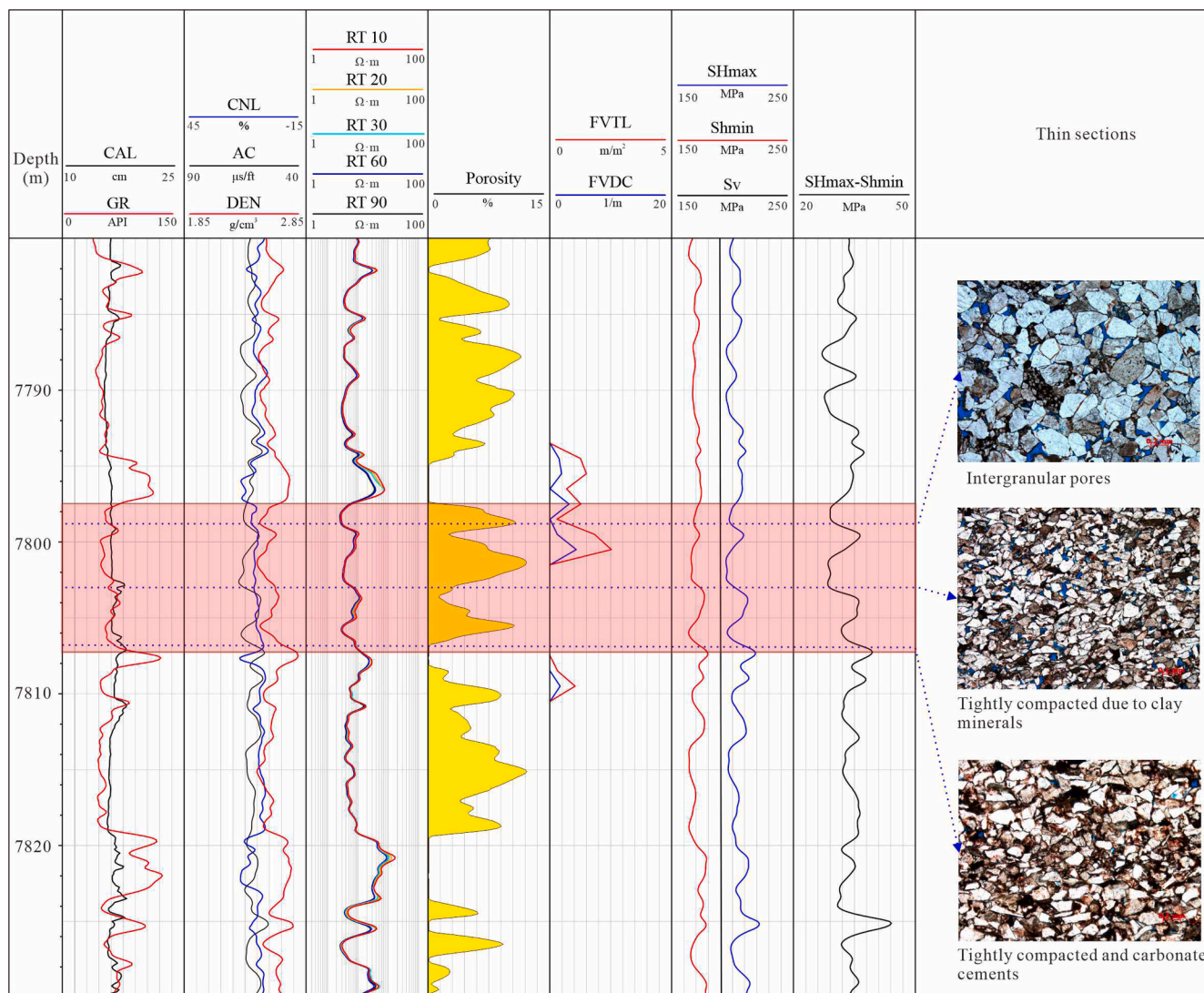


Fig. 16. Reservoir quality evaluation by integrating fracture, diagenetic and in situ stress in the Kuqa Depression (Well Bozi 9).

5.4. Reservoir quality evaluation and implications

Variations in reservoir quality of deep and ultra-deep sandstones reflect complex interrelationships between depositional composition and texture, diagenetic modification, fractures as well as in situ stress (Higgs et al., 2017; Lai et al., 2023b) (Fig. 15). The combination of tectonic factors (paleo stress, in situ stress and formation of fractures), depositional factors (sandstone composition and texture) as well as diagenetic factors (compaction and cementation) contributes to the wide variations of fracture-pore-throat systems in different gas fields in the Kuqa Depression (Fig. 15).

Depositional microfacies and diagenetic modifications as well as in situ stress determine the matrix reservoir quality, while fractures improve fluid flow capacity by constating fracture-pore-throat networks. Medium to coarse grained sandstones deposited in high energy distributary channel microfacies, are clay free and have the ability to inhibit compaction, they will contribute to a high matrix reservoir quality if they are not cemented by carbonate cements (Fig. 16). The high porosity intervals in the Fig. 16 are always those low GR layers with box-shape. However, differences of composition and texture in these sandbodies will result in variations of diagenetic modification, and therefore porosity is also significantly varied inside these sandbodies (7798–7807 m) (Fig. 16).

Microscopic thin section analysis reveals that the sandstones

adjacent to the overlying mudrocks tend to have more carbonate cements since the Mg^{2+} and Ca^{2+} will charge from the mudrocks into the sandstones during burial (Mansurbeg et al., 2008; Loyd et al., 2012). In addition, in a single distributary channel sandbody, clay-rich successions are more compacted due to the strong stress (Fig. 16).

Natural fractures will significantly improve reservoir quality and hydrocarbon productivity (Ameen and Hailwood, 2008; Laubach et al., 2019; Nian et al., 2021; Lai et al., 2021; Zeng et al., 2023; Su et al., 2024). The intervals with natural fractures in the Keshen and Bozi-Dabei gas fields will constitute fluid-flow conduits by connecting the matrix pore throats, forming favorable fracture-pore-throat (Fig. 16). High quality intervals are related to the medium-coarse grained, well sorted sandstones, which are clay-free and cement-free, and additionally, the in situ stress is low, and intergranular pores are well preserved or fractures are formed.

Reservoir properties are the comprehensive reflections of initial depositional composition and texture, subsequent diagenetic modifications, and structural factors including fracture and tectonic stress. Understanding the reservoir property variations and further unravelling the formation mechanisms of fracture-pore-throat system variations will help reservoir quality evaluation and hydrocarbon exploration in deep and ultra-deep sandstones worldwide.

6. Conclusion

Reservoir properties (fracture-pore-throat systems) of the Cretaceous Bashijiqike Formation in the Kelasu and Qiulitage structural belts of Kuqa Depression are varied significantly. The Zhongqiu 1 gas field in the Qiulitage structural belt has the highest matrix porosity, while the matrix porosity of Keshen gas field in the Kelasu structural belt is low. The Bashijiqike sandstones in the Keshen and Bozi-Dabei gas fields of the Kelasu structural belt are heavily fractured, while no evident fractures are detected in the Zhongqiu 1 gas field of the Qiulitage structural belt.

Pore spaces in the Keshen gas field mainly include intergranular and intragranular pores and microfractures, while the pore systems are dominantly of residual intergranular pores and microfractures in the Bozi-Dabei gas field. Abundant intergranular pores are observed in the Zhongqiu 1 gas field. Pore throat sizes in the Keshen gas field are tiny, and are narrow in the Bozi-Dabei gas field, then they become relatively wide in the Zhongqiu 1 gas field.

Fractures in the Keshen and Bozi-Dabei gas fields connect the poor pore throats, thus constituting a favorable fracture-pore-throat network. The connective pore throats in the Zhongqiu 1 gas field will result in a high hydrocarbon productivity even without the fracture contribution.

The paleo stress in the Kelasu structural belt is much higher than the Qiulitage structural belts, and fractures are more abundant in the Keshen and Bozi-Dabei gas fields, while fractures in the Zhongqiu 1 gas field are rare. Formation of fractures implies the release of paleo stress, and intervals with low stress magnitude are favorable for porosity preservation. Relatively high quality reservoirs are mostly associated with the low in situ stress.

Depositional composition and texture exert a primary role in reservoir quality. Medium to coarse-grained and well sorted sandstones have more intergranular pores, while poorly sorted or fine-grained sandstones are tightly compacted due to the overburden stress and additionally horizontal stress.

Degree of compaction and compactional porosity loss is intensive in fine-grained or poorly sorted or clay-rich rocks. Natural fractures in the Keshen and Bozi-Dabei gas fields promote carbonate cementation along the fracture planes, and sandstones in the Keshen and Bozi-Dabei gas fields more cemented. High quality intervals are those clay-free and well sorted sandstones, and intergranular pores are well preserved or fracture are formed due to low in situ stress.

CRedit authorship contribution statement

Jin Lai: Writing – review & editing, Writing – original draft. **Lu Xiao:** Data curation. **Xiangyu Song:** Methodology, Investigation. **Xun Yang:** Software. **Yi Xin:** Methodology, Investigation. **Ronghu Zhang:** Validation, Resources. **Kang Bie:** Validation, Software. **Qinglu Zeng:** Investigation. **Guiwen Wang:** Project administration, Investigation. **Ziqiang Qin:** Software, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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