Research Article

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Fracture characteristics from outcrops and its meaning to gas accumulation in the Jiyuan Basin, Henan Province, China

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Abstract: The target Oil-Shale Member (TOSM) in the Upper Triassic Tanzhuang Formation in the Jiyuan Basin is about 140 m thick and its burial depth is generally between 3,000 and 7,000 m. This paper presents a study of fractures in outcrop analogs for the TOSM based on outcrop observations and experimental measurements. The role of fractures in gas accumulation in the Jiyuan Basin was also analyzed. Also, a workflow used in building discrete fracture models based on the outcrop observed data is described. Results show that the average total organic carbon content and vitrinite reflectance of the oil shale are 4.13 and 1.33%, respectively, with the organic matter type dominated by sapropel-humics (II₁), indicating high potential for shale gas generation. Fracture characteristics showing mostly vertical or intersect the bedding at high angles, and partially unfilled. The fracture lengths and widths range from a few centimeters to several hundred meters, and 0.05 to 0.5 cm, respectively, and the average linear fracture density is 6.3 m. In addition, the average brittle-mineral content of the oil shale is 53.7%, indicating that the oil shale in the TOSM has strong fracability. The hydrocarbon generation occurred twice in the TOSM. The primary reservoir formed by the first hydrocarbon

generation was destroyed by fractures and tectonic uplift, and partial hydrocarbon migrated to the Paleogene along the second-phase fractures to form a secondary reservoir. The gas formed by the second hydrocarbon generation was mainly migrated into the fracture network of the TOSM.

Keywords: Jiyuan Basin, Oil-Shale Member, fractures, gas accumulation, fracability

1 Introduction

Shale gas is an important unconventional gas resource [1], which is formed as a self-generated and self-stored reservoir [2,3]. Since the late 1990s, when Mitchell Energy and Development Corporation made a technological breakthrough in the exploitation of shale gas from Barnett Shale in the Fort Worth Basin, a new era has started for shale gas exploitation in the United States [4]. This technological breakthrough yielded large-scale commercial shale gas exploitation and revolution [5,6]. The reported technically recoverable shale gas resources are 214.5 trillion cubic meters in the world based on the resources investigation results released by the United Nations Conference on Trade and Development in May 2018 [7]. Shale gas has great potential for exploration and development.

Being a fine-grained sedimentary rock characterized by low porosity and permeability, shale is a dual-porosity reservoir composed of matrix pores and fractures [8,9]. Pores determine the volumes of oil and gas while fractures are responsible for oil and gas transport [10]. The fractures are important for shale gas reservoirs investigation [11,12]. The development degree and distribution pattern of fractures are the main factors controlling shale gas accumulation [13,14], which also determine the quality of the shale gas reservoirs [15–17]. Because of shale low permeability, shale gas reservoir is normally hydraulically fractured. However, the shape, orientation, filling characteristics, and density of natural

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fractures in shales have significant influences on the effectiveness of hydraulic fracturing [4]. The study of fractures characteristics is helpful to the evaluation of exploration and development potential [18].

The target Oil-Shale Member (TOSM) in the upper Triassic Tanzhuang Formation in the Jiyuan Basin of China was formed at the peak of hydrocarbon generation [19]. The TOSM is also the most favorable shale deposit for oil and gas exploration and development in the Jiyuan Basin [20]. Within this TOSM, multiple oil and gas shale layers were formed with relatively well-formed tectonic fractures [21,22]. Previous oilfield exploration indicated a good oil and gas potential of these systems but explorers were unable to obtain economic gas production due to the poor physical properties of these shale systems [19,20]. With the advancement of shale gas theory and exploitation techniques, oil and gas exploration in the Jiyuan Basin has drawn renewed interest [23]. Systematic research on the tectonic fractures can provide some insights for the exploration and development of shale oil and gas in this region.

This paper presents a study in the TOSM for the geological characteristics, fractures characteristics, fractures types, and the relationship between fractures and hydrocarbon accumulation based on outcrop observation, sampling, experimental measurements, and system analyses. Note that outcrop fracture studies have great potential to be misleading and the validity of outcrops as guides to the subsurface needs to be studied before the usage of this method [24]. The geological characteristics including petrological, mineralogical characteristics, total organic carbon, types, and maturity of organic matter were analyzed based on these experimental measurements. Outcrop observation and measurements were used to study the orientation, dip angle, length and widths, density, and types of fractures. The relationship between fractures and hydrocarbon accumulation is analyzed systematically. The outcrop of the TOSM is regarded as an analog for the shale reservoirs in this region. Here we show that the results can be used for unconventional oil and gas exploration and development in this region.

2 Geological setting

2.1 Structural environment

The Jiyuan Basin is located on the northwestern edge of the southern North China Basin [21]. The Jiyuan

Basin bordered by the Qinling-Dabie orogenic belt to the south, the Taihang Mountains to the northwest, and the Bohai Bay Basin to the east [25]. The basin belongs to a sub-tectonic unit in the western part of Kaifeng Basin [25]. The Jiyuan Basin is bounded to the southern Taihangshan fault, the eastern Wuzhi fault, the northern Mangshan fault, and the western Xiguo fault [23]. The fault in the Jiyuan Basin generally has NE-SW, E-W, and NW-SE strikes, and these faults cut the basin into a series of secondary folds and fault blocks (Figure 1) [23].

2.2 Geological history and stratigraphic characteristics

From the Late Carboniferous to the Cisuralian period, under the influence of the Hercynian tectonic movement, seawater migrated from the northeast to the southwest, which yields the sedimentation on the whole North China Platform, forming a composite sedimentary system that consists of various facies such as barrier islands, lagoons, tidal flats, and terraces [26]. During the Guadalupian period, due to the end of sea transgression and the beginning of sea regression, combined with the continuous uplift of the northern part of the North China Platform, a delta sedimentation-dominated coal-bearing formation was formed with a total coal seam thickness of 8–20 m [27]. In the Lopingian period, the sea regression continued and the collision between the Qinling microplate and the North China Plate intensified [28]. Some areas uplifted into mountains and red river/lake clastic sediments were deposited under arid climate conditions, and the North China Basin entered the craton inland depression basin evolutionary stage [29]. In the Triassic period, a set of exceptionally thick lacustrine sediments was deposited in the Jiyuan Basin and its surrounding areas, with a total thickness of more than 2,300 m, and up to 3,260 m in the thickest part in the west [23]. The thickness of the dark shales was over 400 m, of which the Tanzhuang Formation Oil-Shale Member is the most developed one, and this physically allows the formation of shale gas [19]. In the Early Jurassic to the Middle Jurassic period, with the uplift of Songji and Shanxi, compensation effects strengthened, the lakes gradually shrank and formed a set of shallow lake-fluvial facies clastic deposits [20]. At the end of the Middle Jurassic period, the western area of Henan Province was uplifted and subjected to

Figure 1: (a) Location of the Jiyuan Basin in China (after Yang and Du, 2017); (b) geological outline map of the Jiyuan Basin and the study area (after Lin et al., 2013); (c) a cross-section, location is shown in B, through the Jiyuan Basin shows the structures and stratigraphy in the study area (after Qi et al., 2009). In Figures: Q + N = Neogene + Quaternary; E = Paleogene; K = Cretaceous; J = Jurassic; T₃ = Upper Triassic; T₁₊₂ = Lower and Middle Triassic; C + P = Carboniferous + Permian; E + O = Cambrian + Ordovician; Ar = Archean; Ce = Cenozoic.

erosion, ending the development of the lacustrine basin (Figure 2).

2.3 Outcrops

The TOSM in the Jiyuan Basin has conformable contact with the underlying Lower Member of the Upper Triassic Tanzhuang Formation and shows parallel unconformity contact with the overlain Lower Jurassic Anyao formation (Figure 2). The buried depth of TOSM is relatively shallow in the west of the Jiyuan Basin, generally ranging from 1,000 to 3,000 m, while the buried depth in the central and eastern Jiyuan Basin can reach 3,000 to 7,000 m (Figure 1). The TOSM in the west of the Jiyuan Basin is well exposed due to the influence of Xiguo Fault (Figure 1). The outcrops No. 1 and 2 are located at the quarries of

4,000 and 500 m away from the Chengliu town, Jiyaan city, respectively (Figure 3a). Impacted by the stone exploitation activities, the fracture characteristics and linear density can be overserved and measured layer by layer (Figure 3b and c). Meanwhile, rock samples weakly influenced by the weathering effect were selected for tests (Figure 3d and e).

3 Methodologies

3.1 Outcrop observations, measurements, and statistics

To study the characteristics of tectonic fractures, we also measured and described the occurrences, lengths, widths,

Figure 2: A schematic diagram showing the stratigraphy of the Phanerozoic and the lithofacies of the Oil-Shale Member of the Upper Triassic Tanzhuang Formation in the Jiyuan Basin (after Zhang, 1997).

filling, and linear density of the fractures. A total of 51 tectonic fracture measuring points in the TOSM were surveyed (see Figure 2 for their positions), and 1,071 tectonic fractures were measured. Based on the previous studies on fracture stages and hydrocarbon generation history, the relationship between fractures evolution and gas accumulation was found.

3.2 Mineralogical analysis

With the help of D/max-ra X-ray diffractometer from Rigaku Corporation (Japan), 18 oil shale samples from the outcrop were analyzed for various minerals in the Shanxi Geological and Mineral Research Institute, China. The analysis was performed following the enterprise standard of the

Figure 3: (a) Associated outcrop location of the study area located in the west of the Jiyuan Basin; (b) the location of fractures linear density measurement points in outcrop 1; (c) the location of fractures linear density measurement points in outcrop 2; (d) an inspection point at outcrop No. 1; (e) an inspection point at outcrop No. 2.

National Energy Administration of China (NEA) SY/T5163-2018. The analysis was based on the principles from Chung and Guo [28,30,31].

3.3 Total organic carbon test

With the CS-200 carbon–sulfur analyzer by LOCE (United States), 22 oil shale samples from the TOSM were analyzed for their total organic carbon contents in the Shanxi Geological and Mineral Research Institute, China. The analysis was performed following the enterprise standard of the National Energy Administration of China (NEA) GB/T19145-2003.

3.4 Organic matter types and maturity

With the Axioskop 2 plus biological microscope by Zeiss (Germany), 10 oil shale samples from the TOSM were analyzed for their organic matter types in the Shanxi Geological and Mineral Research Institute, China. The analysis was performed following the enterprise standard of the National Energy Administration of China (NEA) SY/T5125-2014.

With the MPV-SP microphotometer by Zeiss (Germany), the other 10 samples from the TOSM of the Tanzhuang Formation in the Jiyuan Basin were analyzed for their vitrinite reflectance in the Shanxi Geological and Mineral Research Institute, China. The analysis was performed following the enterprise standard of China National Petroleum Corporation (CNPC) SY/T5124-2012.

4 Results and discussion

4.1 Geological characteristics

4.1.1 Petrological characteristics

The shale formation of the TOSM is mainly composed of oil shale, mudstone, silty mudstone, and siltstone with a total thickness of about 140 m (Figure 2). The total thickness of the oil shale is 66.8 m and the single-layer thickness ranges from 0.1 to 8.4 m. The weathered rock surface is light grey to grey, and the fresh surface is grey to greyish black. The foliation planes show siderite grains,

spores, skin, and wooden remains of ferns, and plants with cone-shaped leaves can be observed in the shale. Fish scale fossils are also present locally. The total thickness of the mudstone is 32.4 m, and the single-layer thickness ranges from 0.1 to 3 m. A weathered rock surface is a greyish-yellow to pale yellow while a fresh surface is a pale yellow. The mudstone has siliceous cementation with both horizontal bedding and massive bedding. Fish scales, conch ostraca, and relatively well-preserved ostracod fossils are present in the mudstone. The total thickness of the silty mudstone is 27.7 m, whereas the single-layer thickness ranges from 0.1 to 2.8 m. The weathered surface is yellow ochre to greyish green and the fresh rock surface is greyish green. Silty mudstone has siliceous cementation with horizontal bedding and massive bedding. Fish scale fossils and near-vertical burrows, *Skolithos*, are visible. The total thickness of siltstone is 15.4 m and the single-layer thickness ranges from 0.1 to 2.8 m. The weathered rock surface is yellow ochre to greyish green and the fresh surface is greyish green. The siltstone has siliceous cementation and is mainly dominated by horizontal beddings. Climbing bedding as well as occasional soft-sediment deformation structures can be observed. Load casts are often present at the bottom of the beds. Trace fossils, *Arenieolites*, and plant debris can be observed in the beds.

4.1.2 Mineralogical characteristics

The content of brittle minerals is an important factor affecting the development of matrix pores and microfractures, fracturing and reforming methods, and gas-bearing property in shale [32]. The higher the content of brittle minerals such as quartz, feldspar, and calcite in shale, the easier it is to form fractures during hydraulic fracturing, and the fractures formed are mostly network fractures, which are conducive to shale gas production [16]. Shale with high clay mineral content has strong plasticity, and the fractures formed under fracturing are mainly plane fractures, which is not conducive to shale volume reconstruction [3]. The brittle mineral content of shale in the Five United States shale formations that presently produce gas commercially is between 46 and 60% [32]. At present, it is generally believed that the brittle mineral content of shale with commercial development conditions is higher than 40% [1].

The results of brittle mineral content test of oil shale in the TOSM of the study area are shown in Figure 4. The minerals of oil shale in the TOSM are mainly quartz, feldspar, clay minerals, carbonate minerals, and siderite. Brittle minerals include quartz, feldspar, carbonate

Figure 4: Mineral composition of 18 shale samples from the TOSM.

minerals, and siderite, and their contents range from 37.4 to 77.9% with an average of 53.7%. The quartz content is between 32.1 and 52.4% with an average of 41.6%. The feldspar content is between 2.8 and 25.7% with an average of 8.4%. Carbonate minerals and siderite can be found occasionally. The clay minerals mainly include interlayered illite/montmorillonite and illite with occasional chlorite. The content of clay minerals ranges from 22.1 to 62.6% with an average of 46.3%. The mineral composition changes show that the TOSM of the Tanzhuang Formation is relatively heterogeneous vertically. The high content of brittle minerals indicates a high friability, and it helps the formation and the propagation of the fractures during subsequent fracturing processes.

4.1.3 Total organic carbon content

Total organic carbon content is an important index to evaluate the abundance of source rocks, and it is also an important parameter to measure the intensity and quantity of hydrocarbon generation [16,33]. Five United States shale formations that presently produce gas commercially exhibit a relatively high total organic carbon content [14]. The total organic carbon content of the Barnett Shale is between 2.0 and 7.0%, with an average of 4.5% [15], the Antrim Shale and New Albany Shale is between 0.3 and 25%, and the Lewis Shale and Ohio Shale is between 0.45 and 4.7% [13]. With the deepening of research, it is generally believed that 0.4 is the lower limit standard of total organic carbon content in shale gas reservoirs [34].

Figure 5: TOC distribution of oil shale samples from the TOSM.

The results of total organic carbon contents of oil shale revealed that the total organic carbon contents of oil shale in the TOSM range from 0.36 to 10.33%, with an average content of 4.13% (Figure 5). Samples with a total organic carbon content greater than 0.4% accounted for 95.5% of the total number of samples. The higher the organic carbon content in the rock is, the more abundant the materials for hydrocarbon generation are. From this aspect alone, it can be concluded that the source rock in the TOSM of the study area is moderate to good.

4.1.4 Organic matter types and maturity

Types and maturity of organic matter are important indexes for the potential evaluation of hydrocarbon generation. The

Table 1: Maturity and types of organic matter for oil shale samples from the TOSM

Sample number	Vitrinite reflectance (%)	Organic types
TZ-1	1.01	II ₁
TZ-2	1.47	III
TZ-3	1.29	II ₁
TZ-4	1.15	II ₁
TZ-5	1.07	II ₁
TZ-6	1.15	II ₁
TZ-7	2.12	II ₁
TZ-8	1.52	III
TZ-9	1.31	II ₁
TZ-10	1.22	II ₁

types of organic matter determine whether the product is dominated by oil or gas, and the maturity of organic matter determines whether the product is in the gas window [34].

The results (Table 1) reveal that the types of organic matter of oil shale are mainly sapropel-humics (II₁), containing a small number of humics (III), the vitrinite reflectance between 1.10 and 2.12%, with an average of 1.33%. By comparing the characteristics of shale reservoirs dominated by gas in the northeast of the Fort Worth Basin, the types of organic matter are mainly sapropel-humics (II₁), and the vitrinite reflectance is between 1.10 and 1.40% [16]. The source rock in the TOSM of the study area has the conditions to generate a large amount of shale gas.

4.2 Fracture characteristics

Characteristics including orientation, length, width, filling, and linear density of fractures are important factors affecting reservoir permeability [18]. Orientation represents the connection between a single fracture and its environment, the fracturing plane can be defined by the strike and dip angle [11]. Lengths are important for quantitatively evaluating their effectiveness as conduits for fluid flow [35]. Widths and filling determine the accumulation and migration of oil and gas [9]. Density is a useful measure of abundance that reports the number of fractures of a given size per unit of rock, the differences in intensity prevalence imply differences in porosity, permeability, and seismic response [36].

4.2.1 Orientation

Rose diagrams based on 1,071 measurements show four dominant strike directions: NNE – SSW, NEE – SSW, NW – SE,

Figure 6: Rose diagram of the 1,071 tectonic fracture from the TOSM.

and NNW – SEE (Figure 6). According to the dip angle, fractures can be divided into four types [11]: vertical fractures (dip angle 75°–90°), high-angle oblique fractures (dip angle 45°–75°), low-angle oblique fractures (dip 15°–45°), and bedding fracture (dip 0°–15°). Vertical fractures are the most common (Figure 7a). There are a total of 583 vertical fractures, 221 high-angle fractures, 169 low-angle fractures, and 98 bedding fractures, accounting for 54.4, 20.6, 15.8, and 9.2% of the total number of the investigated fractures, respectively.

4.2.2 Lengths

Generally, macroscopic fractures can be divided into three types based on their lengths [37]: small fractures (lengths less than 5 m), short fractures (5–50 m long), and long fractures (lengths greater than 50 m). The tectonic fractures in the TOSM are generally small fractures, accounting for more than 65% of the total number of fractures (Figure 7b-a). Therefore, they can influence, to a certain degree, the directionality of the permeability of the entire matrix, which can make the permeability anisotropic. Short fractures account for 25% of the total fractures (Figure 7b-b). If those fractures existed near a well, they might effectively increase early-stage single-well productivity. Long fractures that could affect the well-pattern models are the rarest types, and do not exceed 10% of the total number of fractures (Figure 7b-c).

4.2.3 Filling

Studying on the filling of fractures is important in quantitatively evaluating their effectiveness. Generally, tectonic fractures can be divided into three types based on their filling: unfilled fracture, partly filled fracture, and completely filled fracture [38]. The unfilled fractures

Figure 7: The characteristics of fractures in the TOSM. (a) Vertical and high-angle fractures; (b) different lengths fractures, a: micrometer-scale (fracture lengths less than 5 m), b: short-fractures (5–50 m long), c: long-fractures (fracture lengths greater than 50 m); (c) filling characteristics of fractures, a: completely filled fractures, b: partially filled fractures, c: no-filled fractures; (d) different widths fractures.

possess no deformation or diagenetic material filling, and they are potentially open conduits to fluid flow, whereas completely filled fractures are those filled by secondary or diagenetic mineralization.

Observations of filling characteristics indicate that a total of 547 fractures were completely filled with calcite, zeolite, and quartz (Figure 7c-a), accounting for 51.1% of the total fractures, it has no positive reservoir attributes; 388 of the fractures are partially filled with calcite, zeolite, quartz, and pyrite (Figure 7c-b), accounting for 36.2%, and 136 fractures were not filled (Figure 7c-c), accounting for 12.7%, they have positive reservoir attributes to the rocks in which they reside.

4.2.4 Widths

The fracture widths are important in determining the fracture porosity and permeability. The fracture widths

are relatively small due to the comprehensive action of static rock pressure, formation fluid pressure, and current *in situ* stress. The outcrop fracture widths cannot represent the true widths of underground preservation state of fracture, but the experimentally determined ductilities parallel to those determined from outcrop and underground studies [39], it can still reflect the relative width of underground fracture to some extent.

The widths of fractures in the TOSM are generally between 0.05 and 0.5 cm. Most of them (about 70%) are between 0.05 and 0.1 cm while a minority (about 20%) of fractures are greater than 0.1 cm, with the widest up to 0.5 cm (Figure 7d).

4.2.5 Linear density

In a quantitative study of fractures, the linear fracture density (D_l), areal fracture density (D_a), and volume

Figure 8: The Burial-history diagram and events chart of hydrocarbon in well D5 in the Jiyuan Basin (see Figure 1a for the location; after Qi et al., 2009).

fracture density (D_y) are usually used to characterize the degree of fracture formation [11,38]. We report the linear fracture density (D_l), which is the ratio of the number of fractures intersecting a straight line to the length of the straight line of a lithological layer [40]. The reciprocal linear fracture density is the average spacing of fractures [41]. In different structural positions, the development of fractures varies greatly because of the differences in the lithology, layer thickness, tectonics, and local stress field.

The derived linear density at 51 effective measuring points in the outcrop is generally between 3.0 and 10.5 m. The maximum linear fracture density in certain areas is up to 27.7 m. The average density of fractures in this member is 6.29 m and the tectonic fractures are generally well formed.

4.3 Fractures evolution and hydrocarbon accumulation

The formation, evolution, migration, and accumulation of hydrocarbon reservoirs are very sensitive to tectonic fractures [22,42]. Tectonic fractures formed in different stages have different influences on the migration and accumulation of oil and gas [43–45]. Based on previous studies on hydrocarbon generation history [20] and tectonic evolution history [20], the relationship between structural fracture evolution and oil and gas accumulation was studied, and the evolution history of TOSM in the Jiyuan Basin can be divided into five stages (Figure 8).

Stage I refers to the period before the first hydrocarbon generation, which was from the Late Triassic to the Early Cretaceous, and the first-phase tectonic fractures formed in the TOSM during this period. From the Late Cretaceous to the Middle Jurassic, the Jiyuan Basin was in the evolution phase of the North China Craton, and the paleogeothermal field was steady, with a normal gradient of $3.0^{\circ}\text{C}/100\text{ m}$ [46]. The average depositional rate was about $14\text{ m}/\text{m y}$ from the Late Triassic to the Early Jurassic, and it increased to $37.5\text{ m}/\text{m y}$ from the Early Jurassic to the Middle Jurassic. The TOSM reached the maximum burial depth of approximately $1,100\text{ m}$. From the Middle Jurassic to the Early Cretaceous, the early Yanshanian orogeny caused strong magmatic activity and tectonic changes in Eastern China. The paleogeothermal field in the Jiyuan Basin was abnormal, and the paleogeothermal gradient increased to about $4.29^{\circ}\text{C}/100\text{ m}$ [46]. Under the effect of squeezing, the TOSM experienced a differential uplift, forming a structural pattern of central uplift and north-south depression, with the maximum uplift about 450 m . Meanwhile, the first-phase tectonic fractures with NEE-SWW trending were formed.

Stage II refers to the period where the hydrocarbon generation occurred and reached its first peak, which was during the Cretaceous, and the generated hydrocarbon migrated and accumulated along with the first-phase tectonic fractures in the TOSM during this period. The average depositional rate was about $60\text{ m}/\text{m y}$ in the Early Cretaceous. When the burial depth reached $2,100\text{ m}$, the temperature reached 100°C , and vitrinite reflectance reached 0.6% , it enters the hydrocarbon generation threshold. With the increases of burial depth, the TOSM was buried with the maximum burial depth at most $2,400\text{ m}$, the temperature reached 120°C , and the vitrinite reflectance reached 0.75% . The hydrocarbon generation reached its first peak, which was also the peak of hydrocarbon expulsion and new hydrocarbon filling into the shale, which was the critical moment. On the one hand, the existence of first-phase fractures provided channels for the migration of hydrocarbon, on the other hand, it also improves the reservoir performance. Due to the first-phase tectonic fractures, the hydrocarbon migrated and accumulated along the NEE-SWW trending fractures.

Stage III refers to the period after the first hydrocarbon generation, which was from the Late Cretaceous to the Early Eocene, the second-phase tectonic fractures are formed and destroy the primary reservoir in the TOSM during this period. Because of the Late Yanshanian Period orogeny, the TOSM was uplifted rapidly with the maximum uplift about 950 m , and the source rocks were gradually cooled to stop hydrocarbon generation. Meanwhile, the

second phase of NE-SW trending tectonic fractures was formed. The NE-SW trending fractures cut through the oil reservoirs and seal rock of the TOSM, and the seal rock was also strongly damaged by uplift and erosion, which has a damaging effect on the hydrocarbon reservoirs. The second phase of NE-SW trending tectonic fractures plays a dual role in the formation of oil reservoirs and the redistribution of hydrocarbon. On the one hand, the second-phase fractures cut the first-phase fractures into some new stable fault blocks, and the hydrocarbons were concentrated in these stable fault blocks. These stable blocks were mainly distributed in the central uplift zone (Figure 1b), which can be regarded as the focus of future exploration and development. On the other hand, the second-phase fractures caused some of the oil migrated to the Paleogene to form the secondary reservoir. Well D2 obtained low oil production flow ($0.7\text{ m}^3/\text{d}$), and accumulated oil production of 8.36 m^3 in Paleogene oil test [21]. Based on the analysis of the measure of the gas-liquid inclusion homogenization and the composition of biomarkers in and out of the inclusions in the Paleogene sandstone reservoir of well D2, it is considered that this is a secondary reservoir formed in the Paleogene after the destruction of the primary reservoir in Late Triassic [47]. This secondary reservoir can be regarded as a realistic and economic exploration target series.

Stage IV refers to the period where the hydrocarbon generation occurred and reached its second peak, which was from the Eocene to the Miocene, and the third-phase tectonic fractures were formed during this period, and the hydrocarbon migrated and accumulated along the direction of three-phase tectonic fractures in the TOSM. At this stage, Jiyuan Basin began to enter the stage of fault basin development under the regional extension and tension, and the paleogeothermal gradient also decreased to about $3.3^{\circ}\text{C}/100\text{ m}$ [46]. However, the average depositional rate was about $177.5\text{ m}/\text{m y}$. As the sedimentary thickness in the basin continued to increase, the TOSM was buried with the maximum burial depth at most $4,600\text{ m}$, the temperature reached 160° , the vitrinite reflectance reached 1.4% , and the hydrocarbon generation reached its second peak, which was also the peak of hydrocarbon expulsion and new hydrocarbon filling into the fractures and shale, which was the critical moment. Secondary hydrocarbon is dominated by gas. And then, because of the Early Himalayan Period orogeny, the third phase of NNE-SSW and NW-SE trending fractures were formed. The third-phase fractures and pre-existing fractures cut the TOSM into some new fracture network, large quantities of gas migrated into the fracture network.

Stage V refers to the period after the second hydrocarbon generation, which was from the Oligocene to the

Figure 9: Histogram of fracture density for (a) Outcrop 1 and (b) Outcrop 2.

Table 2: Statistical orientation parameters of different fracture sets

Fracture set	Mean dip, degree	Mean azimuth, degree	Concentration	Statistical method
Fracture set 1	90	105	40	Fisher model
Fracture set 2	90	160	40	Fisher model
Fracture set 3	90	20	40	Fisher model

Holocene. Because of the Early Himalayan Period orogeny, the TOSM was uplifted, with the maximum uplift about 1,200 m in the Oligocene. With the weakening of tectonic activities, the TOSM was slow subsidence, the paleogeothermal gradient was about 2.6°C/100 m, and the average depositional rate was commonly not more than 18.75 m/my from the Miocene to the Holocene. Because the sedimentary thickness was relatively thin, the hydrocarbon generation cannot exceed the thermal evolution degree in the early stage.

4.4 Discrete fracture network (DFN) Modeling

DFN models were built for the two outcrops using a similar workflow reported by Fang et al. [48]. The spatially distributed fracture density is the average of fracture density calculated using equations (2) and (3). The count per meter fracture density is then converted to count per volume fracture density by assuming an average fracture length of 100 m and thickness of 1 m. Results show that

Figure 10: Discrete fracture models for (a) Outcrop 1 and (b) Outcrop 2.

the Outcrop 2 has a higher fracture density than Outcrop 1 because Outcrop 2 is closer to the fault than Outcrop 1 as shown in Figure 3. The average fracture densities are 0.040 and 0.140 count per m^3 (Figure 9). These fracture densities are divided into three equal parts for those three orientated fractures as shown in Figure 6.

Based on the spatially-distributed fracture density, the stochastic fracture model was generated using a commercial geological modeling package. The fractures were shaped in rectangles with the elongation ratio (the ratio of the horizontal length to its vertical length) of 2. The maximum fracture length and the maximum length of implicit fractures are assumed as 1,000 and 100 m, respectively. The fracture length is power distributed with shape and scale parameters of 2.1 and 25, respectively. The parameters for the orientation of three sets of fractures are listed in Table 2.

Figure 10 shows the distribution of DFN models for Outcrops 1 and 2, which indicate a denser fracture distribution at Outcrop 2 than at Outcrop 1.

5 Conclusions

This paper presents a synthetic study on the fractures in the Oil-Shale Member of the Upper Triassic Tanzhuang Formation in the Jiyuan Basin, Henan Province, China. The main conclusions are as follows:

1. The total thickness of the oil shale in the TOSM of the study area is about 66.8 m. The total organic carbon contents and vitrinite reflectance of oil shale are 0.36–10.33% (avg. 4.13%) and 1.10–2.12% (avg. 1.33%), respectively, with the organic matter type dominated by sapropel-humics (II_1), and the brittle-mineral contents of the oil shale are 37.4–77.9% (avg. 53.7%), showing high potential for shale gas generation and good fracability.
2. Fractures in the TOSM are mostly vertical or intersecting with the bedding at high angles, and partially unfilled. The fracture lengths and widths range from a few centimeters to several hundred meters, and 0.05 to 0.5 cm, respectively, and the average linear fracture density is 6.3 m.
3. There were two times hydrocarbon generation occurred in the TOSM. The primary reservoir formed by the first hydrocarbon generation was destroyed by fractures and tectonic uplift, and some of the hydrocarbon migrated to the Paleogene along the second-phase fractures to form a secondary reservoir. Partial gas formed by the second hydrocarbon generation

migrated into the fracture network, which is also the target of future exploration and exploitation.

4. A workflow used in building discrete fracture models based on the outcrop observed data is described. However, more parameters needed to be investigated in the future, for example, fracture length and its distribution.

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