Assemblage of strike-slip faults and tectonic extension and compression analysis: A case study of a Lower Permian commercial coal reservoir in China

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The Qinshui Basin was an active residual basin in the Mesozoic and Cenozoic periods and is located inside the North China Plate. The Upper Paleozoic strata in the basin have been strongly deformed and have developed a large number of strike-slip faults. The Qinshui Basin has been influenced by compressive stress from the northeast direction since the Himalayan period, and the faults have a dextral strike-slip property. Under the action of such a stress field, the right-slip, right-order faults indicate an extension region, and the right-slip, left-order faults indicate a compression region. Based on this principle, the extension and the compression areas were divided. From northwest to southeast direction in the study area, two types of regions have interactive distribution characteristics. For the Fanzhuang block in the eastern part of the study area, the fault distribution has an 'S-type' trend from north to south, and the middle extension region is the 'elbow' or the 'hinge zone' of the 'S-type' area, which can also be called the 'stress transition zone'. The tectonic stress field of the stress transition zone is complex, and tensile fractures are usually extremely developed with extension tectonics. Gas wells with higher capacity are mainly distributed in the extension zone, while the capacity of the gas wells in the compression area is usually lower. The study showed that the distribution of the gas well capacity is consistent with the tectonic extension and compression analysis, indicating that the tectonic analysis method in this study is reliable. The Upper Paleozoic coal measure strata in the Qinshui Basin represent a whole gas-bearing and stress-bearing system, the tectonic analysis method in this study is also applicable to other types of tight reservoirs for this set of depositional systems.

Keywords. Strike-slip fault zone; extension area; compression area; gas controlling effect.

1. Introduction

With the gradual depletion of conventional oil and gas resources, the importance of unconventional oil and gas resources is becoming increasingly

significant (Zou *et al.* 2012; Weijermars 2013; Farrell *et al.* 2014; Li *et al.* 2015; Wang *et al.* 2016; Lv *et al.* 2017). Effective exploitation of unconventional oil and gas can protect the country's natural gas supply and demand balance while enhancing

the country's international energy decision-making capacity (Bocora 2012; Weijermars 2013).

Coal measure strata are widely distributed in the Upper Paleozoic (Carboniferous–Permian) strata of China and have good gas-bearing properties (Dai *et al.* 2014). ‘Coal measure’ is also known as ‘coal series’ or ‘coal-bearing construction’, which refers to a sedimentary rock system containing coal seams or coal lines (Wang *et al.* 2015). Large gas fields in China are mainly composed of coal-derived gases. By 2011, 48 large gas fields had been discovered, 31 of which are coal-derived gas fields (Dai *et al.* 2014; Yin *et al.* 2016). The Qinshui Basin is a residual basin in the eastern part of China, several sets of marine-continental transitional facies coal measure strata were developed in the Upper Paleozoic (Liang *et al.* 2014). The coal measure strata have undergone deep burial, multistage tectonic evolution and strong uplift and denudation in the geological period of history. The enrichment degree of the large-scale distributed natural gas is extremely uneven. For the coal measure tight gas reservoirs, sedimentation is the foundation of reservoir formation, diagenetic reconstruction is an important condition for the formation of high-quality reservoirs, and tectonic action is a leading factor for oil and gas enrichment. Therefore, it is of great practical significance to conduct tectonic analysis of coal measure strata in the strong deformation zone and to study its controlling effects on the tight gas distribution.

The Qinshui Basin is locating as an intra-continental basin in the North China Plate (Tang *et al.* 2006). Since the Indosinian period, being influenced by the combination of the Siberian plate, the Yangtze plate, the remote western Pacific plate and the Indian plate, a series of orogenic belts and deep faults have formed around the Qinshui Basin. The terrains inside the Qinshui Basin have occurred in multiple phases of deformation (Chen 2009). The Qinshui Basin develops many strike-slip faults, and the formation, evolution and distribution of these strike-slip faults have important effects on the fluid migration, reservoir petrophysical properties and the natural gas preservation in the inherited paleo-uplifts (Li *et al.* 2012; Abdunaser and McCaffrey 2015; Twinkle *et al.* 2016).

The tectonic assemblage of the strike-slip fault zone can affect the stress state of the local tectonic unit, resulting in a non-negligible effect on the petrophysical properties of the tight reservoirs (Nickelsen 2009; Nenna and Aydin 2011; Ju *et al.*

2016; Godara *et al.* 2017). For rocks with strong heterogeneity, along the extension direction of the strata, with the change of rock properties, the differential stretching or shearing of strata will have a significant effect on the distribution of faults (Morley 2013; Misra and Gupta 2014; Ozcelik 2016). In this study, taking the coal measure strata of the Lower Permian Shanxi Formation in the southern Qinshui Basin of eastern China as an example, the fault development characteristics in this area are analyzed by using the latest seismic data. On this basis, we discuss in detail the tectonic extension and compression of the strike-slip fault zone in the strong deformation zone and its effect on the productivity of the tight reservoirs. The study will not only guide the oil-gas exploration and development in the coal measure strata, but also enrich the basic theory of oil and gas geology in the complex tectonic zone of a marine-continental transitional facies sedimentary system.

2. Geological background

2.1 Location of the study area

The Qinshui Basin is located in the southern part of Shanxi Province, China and is a large-scale composite anticline basin with a north–south strike. It is surrounded by uplifts, with the uplift of the Taihang Mountains in the east, Lvliang Mountain uplift in the west, uplift of the Zhongtiao Mountains in the south, and Wutai Mountain uplift in the north. The Qinshui Basin is located on the east side of the largest mountain-shaped structure (consisting of Qilan Mountain, the Helan Mountain and Lvliang Mountain) in China. The activity of the Qilan–Lvliang–Helan mountain-shaped structure began in the Late Paleozoic. The embryonic shape was formed in the Mesozoic, and the final shape was formed in the Cenozoic period. The ‘mountain-shaped structure’ is a twisted structure, and its evolution is often associated with large-scale mineral enrichment and oil and gas reservoirs (Ren 1994).

The study area is situated in a well block of coalbed methane in the southern area of the Qinshui Basin, including the Zhengzhuang block and the Fanzhuang block (figure 1a–b). The Upper Paleozoic strata in the study area have experienced multiple tectonic movements, including the Indosinian movement, the Yanshan movement and the Himalayan movement (figure 2). According

Figure 1. Location, tectonic features and well distribution for the study area.

Figure 2. Burial and thermal history evolution of the JS1 well in southern Qinshui Basin (Su *et al.* 2005).

to the latest seismic data interpretation results, high-angle strip-slip faults are present in this area (figure 1c). The majority of these faults strike NE and NNE, with a minority striking N–S and WNW. The elevation of the terrain is generally high in the southeast and low in the northwest.

2.2 Sedimentary system

The stratigraphic column of the southern Qinshui Basin is shown in figure 3. The Shanxi Formation is the target layer of this paper, and the No. 3 coal seam in the Shanxi Formation is the key layer of

Figure 3. Stratigraphic column of the southern Qinshui Basin.

coal-bed methane exploration and development in this area.

The Shanxi Formation in the area is a sedimentary shallow-water delta system, which is dominated by the delta plain and the delta front facies, whereas the front delta facies are not developed. The main sedimentary microfacies are distributary channels, swamps and distributary bay microfacies. The distributary channels are mainly medium coarse-grained cuttings or feldspar quartz

sandstone, the trough and plate-like interlaced beddings are developed, and large-scale, silicified fossils are common to see. The swamp sediments are divided into the lower greyish-black silty shale and mudstone and the upper massive carbonaceous shale. The distributary bay facies are interlayer structures of the lens body sandstone and black shale, and a small amount of plant fossil fragments can be found (Shao *et al.* 2015).

In the Indosinian tectonism, the sedimentary system of the Shanxi Formation has just formed. In the weak extrusion conditions, the Shanxi Formation has a slight deformation. In the early Yanshan movement, the Qinshui Basin was in the evolution stage of compression – twist depression within the craton, the Shanxi Formation has a strong deformation. While in the middle-late Yanshan movement, the basin is in a weak extensional stress environment, and stress relaxation occurred for the Shanxi Formation. In the Himalayan orogeny, the Qinshui Basin was in the evolution stage of strong extensional rifting within the craton. Under the regional crustal compression in the direction of NNE–NE, right-slip strike slip occurred for the faults, and the basin continues to uplift and erode. The Shanxi Formation has undergone a strong deformation.

3. Tectonic evolution of Qinshui Basin

3.1 Indosinian movement

The Qinshui Basin is located in the North China block. Since the Paleozoic, its tectonic development has been dominated by the three global dynamic systems of the Tethys Ocean, the ancient Asian Ocean and the ancient Pacific (Ren 1994). The North China block was in a basically stable sedimentary stage for 1.7 billion years, from the final cratonization in the Early Proterozoic (Pt₁) to the continental break-up in the Mesozoic (Liu 1987). In the Indosinian period, the ancient Asian Ocean drove a demise from east to west as the ‘scissors collision’ occurred between the South China block and the North China block from east to west. In this tectonic context, some folds and thrust faults with near EW strikes were formed in the study area (Zhu *et al.* 2012).

3.2 Yanshan movement

The ‘Yanshan movement’ is a tectonic change in the Late Mesozoic in East Asia, and its effects

Figure 4. Tectonic background of 'East Asia agglomeration' in the Late Jurassic.

were global, as it was an important transition of global deformation after the Pangaea break-up, which had an important influence on the tectonic evolution of the Qinshui Basin (Ren 1994). In the Early Jurassic (J_1), the Taihang Mountains in the east side of the Qinshui Basin had not yet experienced uplift, and the North China craton was influenced by the compression of the Siberian plate and the Indian plate (Deng *et al.* 2006). In the Middle Jurassic (J_2), the tectonic mechanism in eastern China had undergone significant changes. The ancient Asian oceanic tectonic domain in the eastern part of the North China craton gradually changed from the convergence system to the subduction system (Zhang *et al.* 1983). At this time, the ancient Pacific plate subducted strongly under the Eurasian plate, resulting in the extrusion direction suffered by the North China block, which gradually changed to the NW–SE direction (Ren 1994). At the end of the Middle Jurassic (J_2), large-scale uplift and eruption occurred in the eastern part of China, a large number of NE-oriented compressive and high-angle strike-slip faults were formed in North China (Li *et al.* 2012). The Taihang Mountains and Luliang Mountain on both sides of the Qinshui Basin began to rise gradually, and a gentle synclinorium was formed between these two uplift belts, which is the Qinshui Basin (Xia *et al.* 2009). In the Middle-Late Jurassic (J_2 – J_3 , early Yanshan movement), the Qinshui Basin was completely separated from the other basins in North China and became an independent tectonic basin.

Notably, in the Late Jurassic (J_3), the Siberian plate moved southward, the Mongolia–Okhotsk Ocean closed, the Pacific plate moved westward, the coastal Pacific tectonic system formed, the Indian plate moved northward, and the Indian Ocean opened (Zhang *et al.* 1983). Under the combined action of the three plates, the unique multi-directional aggregation structural pattern and the intracontinental orogenic deformation in East Asia were finally formed (figure 4). The beginning time for the 'East Asia agglomeration' is approximately 165 ± 5 Ma (Ren 1994).

In the middle of the Yanshan movement (K_1), the North China region gradually changed to an extended environment, and the corresponding time is approximately 136 Ma, which is mainly based on the distribution of the metamorphic core complex rocks, the extensional structure in the basin and the distribution of the large igneous province and magmatic rock belt in this period (Dong *et al.* 2009). The metamorphic core complex rocks are widely distributed in the surrounding area of the Qinshui Basin (Deng *et al.* 2006), but it has uneven distribution characteristics, which reflects a differential extension of the basin. In the middle-late Yanshan movement (K_1 – K_2), the Qinshui Basin was in an extensional tectonic environment.

3.3 Himalayan movement

Since the Paleogene (E), the cracking of the North China craton occurred, and the 'Fen Wei graben

Figure 5. Plane distribution of the seismic lines in the study area.

system' appeared (Yin *et al.* 2016). At this time, the NW–SE directional extension action mainly occurred in the study area, and a large number of right-slid torsional high-angle faults were formed in the shallow strata (Bryant *et al.* 2004). During this tectonic movement, a strong uplift occurred in the Upper Paleozoic strata of the study area.

Since the Neogene (N), the basins in North China have entered the Craton inner depression development stage. At the beginning of the Pliocene (N_2^1), by the effect of continuous convergence of the Indian continent and the Eurasian continent, the extrusion extended eastward and spread to the Qinshui Basin, causing the resurrection of the right-slip strip-strike of the faults in this area (Zhang and Dong 2008). The Shanxi graben system was eventually formed at this stage (Li *et al.* 2012). In the North China region, a series of mountainous basins being cut into blocks were distributed near the major fault zones. At this time, the sedimentary strata in the Qinshui Basin underwent intense uplift and erosion, and the maximum erosion amount is >3000 m (Yin *et al.* 2016). The whole basin is in an extrusion background, and the strike-slip pull-apart action is a typical, local tectonic feature. Under the action of multi-staged tectonic movements, the present tectonic pattern of the study area was eventually formed.

4. Fault development characteristics

In the study area, there are 95 seismic lines (figure 5). Among them, 66 seismic lines are in the Zhengzhuang block, including 38 main seismic lines and 28 contact lines, with a total length of approximately 1000 km. There are 29 seismic lines in the Fanzhuang block, including 14 north-south main seismic lines, 13 contact lines, and 2 free lines, with a total length of ~ 256.46 km.

4.1 Outcrop profile fault

The Indosinian tectonism, Yanshan movement and Himalayan orogeny have direct effect on the structural evolution of the Qinshui Basin in North China Plate. Subsequently, the area has outstanding geological records in terms of tectonics and structural interference pattern. The significance of the structural elements in the Upper Paleozoic strata within the Qinshui Basin is reflected as the complex geometry inherited since the Indosinian tectonism. The outstanding structural elements within the Qinshui Basin include strong deformation and fault negative inversion (high-angle strike-slip faults).

The results of the field outcrop geological survey in the surrounding area of the Qinshui Basin show that faults are extremely developed and are

Figure 6. The geological section of the Upper Paleozoic Permian strata in the Qinshui Basin. Note: The town of Nanling, Zezhou County, Shanxi Formation, GPS 35°23'5.82"E, 112°42'40.75"N.

primarily high-angle strike-slip faults. The folds in the study area are a series of isopach folds associated with high-angle strike-slip faults (figure 6). The axial direction of the folds shown in figure 6 is in the near-EW direction, which is consistent with the Indosinian tectonic stress field (SN direction), indicating that the Indosinian movement has a certain influence on the formation of the early folds in the study area.

The fault characteristics of the outcrops surrounding the Qinshui Basin are also quite obvious. For example, NE-oriented near-vertical, tensile strike-slip faults are developed in the shallow strata of the Taihang Mountain fault zone on the eastern side of the Qinshui Basin. These high, steep, tensile strip-strike faults are superimposed on the Middle-Late Jurassic (J_{2+3}) thrust faults (figure 7) (Cao *et al.* 2013), which indicate that the local area of the basin is in a tensile-stress field, and the faults have undergone a strong negative reversal.

The high-angle base-surface strike-slip faults developed in the study area control the formation and development of the descent plane (upper plate) positive traction folds and the ascending plane (lower plate) isopach folds (figure 8). The NE-trending faults formed from the thrust faults began in the early Yanshanian period and were gradually transformed into the present high-angle strike-slip faults in the late Yanshanian and Himalayan periods (Cao *et al.* 2013).

From the QS08-97 seismic line profile in figure 9, it can be seen that the Upper Paleozoic

strata in the study area are strongly deformed, the terrain and the graben are interphase distributed, and the negative flower structures are developed. The negative flower structure is also an important sign that the fault has a strike-slip property (Cundall and Hart 1985). Larger graben generally forms in the interior of the two large strike-slip faults, and the strata in the graben typically have severe deformation and subsidence. The two largest boundary faults (Sitou fault and Houchengyao fault) in the region are high-angle strike-slip faults. The formation near the Sitou fault has significant deformation; a large graben formed between the Sitou and Houchengyao faults. This graben extends through the entire southeast area of the Zhengzhuang block (figure 9).

4.2 Fault plane distribution

The schematic diagram of strike-slip fault geometry for the Qinshui Basin is shown in figure 10. The plane distribution forms of the faults are primarily S-type, anti-S-type, and en-echelon type (figure 11). These features are important markers in identifying strike-slip structures on a plane. In the study area, the NE, NEE, NNE and NNW faults are predominantly developed (figure 11). Among them, the NE faults have the highest degree of development.

High-angle strike-slip faults are extremely developed in the study area, and some of the faults cut through the entire strata to the surface. The

Figure 7. The characteristics of the NE-oriented faults in the area of the Taihang Mountains, eastern Qinshui Basin (Cao *et al.* 2013). Note: (a) East Sijiashui village fault, GPS N40° 5.785', E115° 57.421'; (b) Zijinguan fault in Zhaogezhuang, GPS N39° 41.423', E115° 18.988'.

opening fault is detrimental to the preservation of tight gases. Therefore, in tight gas exploration, the adverse effects of this type of fault should be considered. However, near the opening faults, the petrophysical and fluid seepage properties of the tight reservoirs have improved. The inner area of the strike-slip fault zone remains an important area for oil and gas exploration (Liu *et al.* 2015).

Based on the fault scale (extension distance, vertical fault throw and disconnected horizon) and the fault control effects on the tectonics and sediments, faults in the study area were divided into three grades (figure 11): (1) Second-grade faults, such as the Sitou and Houchengyao faults are boundary faults of the secondary tectonic unit in the basin, belonging to the 'belt' control faults. (2) Third-grade faults are local tectonic boundary faults. The fault scale is small, belonging to the 'trap' control fault. (3) Fourth-grade faults are predominantly secondary faults that are induced by

the primary faults and have a regulatory role in the release of tectonic stresses. The fourth-grade faults can increase the complexity of the local strata structures, and their overall strikes are consistent or oblique to the primary faults. Figure 10 shows that the fourth-grade faults are the predominant fault types that developed in this area.

5. Effect of tectonic extension and compression on coal reservoir productivity

5.1 Strike-slip compression and extension domains and mechanism of oil and gas enrichment

Strike-slip faults are mostly related with the 'Himalayan orogeny' in this study area. They can also be described as strike-slip restraining

Figure 8. Interpreted seismic profile of the QS08-89.5 seismic line. Note: The seismic reflection interfaces T'_5 , T_5 , T_6 , T_7 , T_8 and T_g represent the tops of the Xiashihezi Fm. (P_{1x}), Shanxi Fm. (P_{1s}), No. 3 coal seam ($3^\#$), Taiyuan Fm. (C_{3t}), No. 15 coal seam ($15^\#$) and Middle Ordovician (O_2), respectively.

Figure 9. Interpreted seismic profile of the QS08-97 seismic line. Note: The seismic reflection interfaces T'_5 , T_5 , T_6 , T_7 , T_8 and T_g represent the tops of the Xiashihezi Fm. (P_{1x}), Shanxi Fm. (P_{1s}), No. 3 coal seam ($3^\#$), Taiyuan Fm. (C_{3t}), No. 15 coal seam ($15^\#$) and Middle Ordovician (O_2), respectively.

Figure 10. Schematic diagram of strike-slip fault geometry for the Qinshui Basin.

Figure 11. Distribution of different fault grades in the study area.

and strike-slip releasing domains within the overlap zone in between two parallel strike-slip faults or shear zones. The fault pattern also can be defined as ‘Relay Fault’ geometry which is very well known in oil industry (Yin *et al.* 2016).

For large scale faults, such as first-grade and second-grade faults, strike-slip faults can lead to significant stress plane heterogeneities. There may be obvious stress variation on both sides of a fault, which will further affect the enrichment of oil

Figure 12. Tectonic assemblage of strike-slip faults and its effect on the formation stress environment.

and gas. However, fourth-grade faults are mainly developed in the study area, and the change of the stress caused by the small faults is small. Therefore, this paper mainly analyzes from the perspective of the overall tectonic environment.

Tectonic extension and compression affect the distribution of stress, which will further affect the enrichment of oil and gas. In the compression region, the petrophysical properties of the reservoir is tight, which are not conducive to the enrichment of tight gases. For the strongly deformed region with obvious compression action in the study area, opening strike-slip faults are usually developed, which are not conducive to the preservation of tight gases. While in the extension region, the *in-situ* stresses are smaller and the reservoir compaction degree is low. The *in-situ* stresses indicated here are mainly horizontal stresses, including the maximum horizontal principal stress and the minimum horizontal principal stress. For tight reservoirs, the maximum horizontal stress determines the extension direction of the fractures, while the minimum horizontal stress determines the opening direction of the fractures (fracture aperture) within the reservoir. Therefore, the reservoir in the extension areas will have a smaller compaction degree, better petrophysical properties and higher permeability, which are beneficial for the enrichment of tight gases. During the tectonic evolution, the tectonic compression and extension are a long-term process, while the migration and accumulation of oil and gas are a dynamic process. In this evolutionary process, hydrocarbons are continuously transported from high stress domains to low stress domains, the

tectonic compression and extension have a significant impact on the final distribution of the tight gases in this area.

According to the arrangement of the strike-slip faults, the tectonic stress environment of the formation can be designated (Prante *et al.* 2014). As shown in figure 12, in the left-slip, left-order and right-slip, right-order strike-slip fault combination conditions, the inner strata of the fault zone have an extensional trend, which represents the extension area, whereas in the left-slip, right-order and right-slip, left-order strike-slip fault combination conditions, the internal strata of the fault zone have a tendency toward compaction, which represents the compression area (Cundall and Hart 1985). It is clear that the petrophysical properties of the tight reservoir in the extension zone are significantly better than the compression zone reservoir, in which it is easier to get a high yield.

5.2 Results and analysis

At present, the Permian Shanxi Formation coalbed methane in the study area is under commercial development (Dai *et al.* 2014). Therefore, based on the coalbed methane production data in this area, we analyzed the distribution of the gas well productivity and then verified the tectonic extension–compression effect of the strike-slip fault zone. The Upper Paleozoic coal measure strata in the Qinshui Basin is a whole gas-bearing and stress-bearing system (Liang *et al.* 2014). Thus, the tectonic analysis method in this paper is also applicable to other

Figure 13. The division results of the extension and compression regions in the study area.

types of tight reservoirs for this set of depositional systems.

The southern part of the Qinshui Basin was mainly subjected to the north-west compressive stress in the Yanshanian period, and a series of compressive torsional left slip, strike-slip faults formed (Nenna and Aydin 2011; Cao *et al.* 2013). Being influenced by the left slip, strike-slip and stretching stress in the middle-late Yanshanian period, the early compressive torsional fault began to occur in a negative reversal (Nenna and Aydin 2011). Since the Himalayan period, the Qinshui Basin has been mainly affected by the compressive stress from the northeast direction, and the faults have right-slip, strip-strike properties (Chen 2009; Li *et al.* 2012). In such a tectonic environment, we can see from figure 13 that the right-slip, right-order fault combination represents the extension area, while the right-slip, left-order fault combination represents the compression area.

According to the strip-strike fault arrangement principle, the tectonic extension area and the compression area of the local area of the study area were divided, which is shown in figure 13. The faults of the large areas in the northwestern part of the study area have a significant right-slip,

right-order property, representing the extension area. The banded area close to this extension area in the southeastern direction is a compression area. Continuing to the southeast direction are an extension area and a convergence area, respectively. The Sitou–Houchengyao strike-slip fault zone is a convergence area, the faults have obviously right-slip, left-order property. In the eastern part of the study area (Fanzhuang well block), the faults on the north and south sides have the right-slip, left-order property, indicating the compression area, and the faults in the central area have the right-slip, right-order property, indicating the extension area.

From the northwest to the southeast direction, the extension area and the compression area have the interactive distribution characteristics. For the Fanzhuang block in the eastern part of the study area, from the north to the south, the faults have a trend of an ‘S-type’ orientation, and the middle extension area is the ‘elbow’ or ‘hinge zone’ of the ‘S-type’ region. These areas are usually called the ‘stress transition zone’, which has a complex tectonic stress field, and fractures are usually much more developed with stretching tectonics (Pei *et al.* 2015).

Table 1. Statistical results of gas well capacity distribution in extension and compression areas.

Area type	No. of high-yield wells	No. of middle-yield wells	No. of low-yield wells	Ratio of high-yield wells (%)	Drilling success ratio (%)	Drilling loss ratio (%)
Extension area	12	7	1	60	95	5
Compression area	1	11	13	4	48	52

Note: Capacity of high-yield wells is $>2000 \text{ m}^3 \cdot \text{d}^{-1}$, capacity of middle yield wells is between 1000 and $2000 \text{ m}^3 \cdot \text{d}^{-1}$, and these wells are general or normal-yield wells. Capacity of low-yield wells is between 0 and $500 \text{ m}^3 \cdot \text{d}^{-1}$, and these wells are mainly dry wells.

There are two large-scale faults in the study area, that is, the Sitou fault and the Houchengyao fault. These two faults have large intensity and are both opening faults. Their existence accelerates the dissipation of tight gases. This area is located in the extrusion area, strong extrusion is an important reason for the formation of the large-scale fault. For the other regions, some smaller fourth-grade faults are mainly developed, and the capping ability of the cap layer has not been destroyed (Yin *et al.* 2017). Therefore, hydrocarbons near these faults can be trapped. At present, the effect of strike-slip faults on oil and gas distribution in this area is still at a preliminary stage, we think these small faults improve the petrophysical properties of the surrounding reservoirs, especially the permeability. Therefore, it is easier to obtain high-yield wells in the extension and small scale strike-slip fault zone.

We used the CBM productivity data in this area to verify the results, as shown in table 1. The proportion of high-yield wells in the extension area is high, reaching 60%; the drilling success rate is as high as 95%; and the proportion of the drilling loss is only 5%. The proportion of high-yield wells in the compression area is only 4%; the drilling success rate is only 48%; and the proportion of drilling loss is high, reaching 52%. It can be seen that gas wells with higher productivity are mainly distributed in the extension area, while the productivity of the gas wells in the compression area is low. The distribution of gas well productivity is consistent with the abovementioned tectonic extension–compression analysis, which verifies the reliability of the tectonic analysis method in this paper.

6. Conclusions

- The Qinshui Basin is located in a complex tectonic belt, faults are extremely developed and are primarily high-angle strike-slip faults. The folds in the study area are a series of isopach folds associated with high-angle strike-slip faults. The high-angle base-surface strike-slip faults control the formation and development of the descent plane (upper plate) positive traction folds and the ascending plane (lower plate) isopach folds.
- The Upper Paleozoic strata in the study area are strongly deformed, the terrain and the graben are interphase distributed, and the negative flower structures are developed. The negative flower structure is also an important sign that the fault has a strike-slip property. The plane distribution forms of the faults are primarily S-type, anti-S-type, and en-echelon type. In the study area, the NE, NEE, NNE and NNW faults are predominantly developed. Among them, the NE faults have the highest degree of development.
- Since the Himalayan period, the strip-strike faults in the Qinshui Basin have a dextral strike-slip property. According to the arrangement of the strike-slip faults, under the action of such a stress field, the right-slip, right-order faults indicate an extension region, and the right-slip, left-order faults indicate a compression region.
- The tectonic extension area and the convergence area of the study area were divided. From the northwest to the southeast direction, the extension area and the compression area have interactive distribution characteristics. For the Fanchang block in the eastern part of the study area, from north to south, the faults have a trend of an ‘S-type’ orientation, and the middle extension area is the ‘elbow’ or ‘hinge zone’ of the ‘S-type’ region. These areas are usually called the ‘stress transition zone’, which has a complex tectonic stress field, and fractures are usually much more developed with extension tectonics.
- Gas wells with higher productivity are mainly distributed in the extension area, while the productivity of the gas wells in the compression

area is low. The distribution of gas well productivity is consistent with the abovementioned tectonic extension–compression analysis, which verifies the reliability of the tectonic analysis method in this study.

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