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Hydrocarbon migration and accumulation along the fault intersection zone—a case study on the reef-flat systems of the No.1 slope break zone in the Tazhong area, Tarim Basin

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Abstract: Understanding hydrocarbon migration and accumulation mechanisms is one of the key scientific problems that should be solved for effective hydrocarbon exploration in the superimposed basins developed in northwest China. The northwest striking No.1 slope break zone, which is a representative of superimposed basins in the Tarim Basin, can be divided into five parts due to the intersection of the northeast strike-slip faults. Controlled by the tectonic framework, the types and properties of reservoirs and the hydrocarbon compositions can also be divided into five parts from east to west. Anomalies of all the parameters were found on the fault intersection zone and weakened up-dip along the structural ridge away from it. Thus, it can be inferred that the intersection zone is the hydrocarbon charging position. This new conclusion differs greatly from the traditional viewpoint, which believes that the hydrocarbon migrates and accumulates along the whole plane of the No.1 slope break zone. The viewpoint is further supported by the evidence from the theory of main pathway systems, obvious improvement of the reservoir quality (2-3 orders of magnitude at the intersection zone) and the formation mechanisms of the fault intersection zone. Differential hydrocarbon migration and entrapment exists in and around the strike-slip faults. This is controlled by the internal structure of faults. It is concluded that the more complicated the fault structure is, the more significant the effects will be. If there is a deformation band, it will hinder the cross fault migration due to the common feature of two to four orders of magnitude reduction in permeability. Otherwise, hydrocarbons tend to accumulate in the up-dip structure under the control of buoyancy. Further research on the internal fault structure should be emphasized.

Key words: Geologic chromatographic effect, fault intersection zone, differential hydrocarbon migration and accumulation, superimposed basin, Tazhong area, Tarim Basin

1 Introduction

Faults have always been a controversial and difficult topic in petroleum geology, because they control not only the formation and evolution of basins, but also the essential factors and processes of petroleum systems (Sorkhabi and Tsuji, 2005). Since the 1980s, there have been overall 11 AAPG annual meetings and 14 AAPG memoirs that focused on fault-related problems (Sorkhabi and Tsuji, 2005). The superimposed basin refers to a basin overlapped by two or more types of primary basins (Jin and Wang, 2004; He et al, 2004). The geological conditions of superimposed basins in China are very complicated. They are characterized by multi-phase formation, multi-phase superimposition of primary basins, multi-episode structural movements, and multi-period and multi-order unconformities (He et al, 2005; Jia et al, 2007; Tang and Jia, 2007). Correspondingly, there are multiple sets of source rocks, and the formation of reservoirs is characterized by multi-phase hydrocarbon generation, expulsion, migration and accumulation. Subsequently, the hydrocarbon reservoirs underwent multi-period adjustment and reconstruction (Jin and Wang, 2004; Jia et al, 2005; Pang et al, 2007). The fault systems in the Tarim Basin can be divided into five sub-fault systems: the surrounding fault system, the foreland basin, the northern uplift zone, the central

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uplift zone, and the southern uplift zone. The No.1 slope break zone is representative of the fault systems developed in the central uplift zone. It is valuable to study its effect on hydrocarbon migration and accumulation during multi-period and multi-episode tectonic activities. The research results will help to solve the problems about hydrocarbon accumulation mechanisms and guide the hydrocarbon exploration in the superimposed basins in northwest China (Jin and Wang, 2004).

Hydrocarbon accumulation mechanisms and processes in the Tazhong No.1 slope break zone are complicated. The hydrocarbon was sourced from the mixed source rocks of the Cambrian–Lower Ordovician and the Middle-Upper Ordovician (Li et al, 2008a) and multi-phase hydrocarbon charging occurred at middle Caledonian, late Hercynian and Himalayan stages (Han et al, 2008). The reservoirs formed each time were then adjusted and reconstructed at middle Caledonian, late Caledonian and late Yanshan periods. Although researchers have analyzed the hydrocarbon generation, migration and accumulation from different aspects (Wu et al, 2005; Han et al, 2008; Chen et al, 2008), the following problems still remain controversial:

1) Contributions of the No.1 fault to hydrocarbon accumulation. Most researchers hold the view that hydrocarbon migrates vertically along the fault plane and accumulates in the Tazhong No.1 slope break zone, but this model can not explain the observed hydrocarbon enrichment distribution well. For example, oil accumulated in the west while gas predominated in the east. Whether there exists large-scale lateral migration from west to east is still controversial (Liu et al, 2008; Guo et al, 2008).

2) Hydrocarbon accumulation mechanisms are unknown. All the reservoirs are distributed at a height difference of 2,500 m along the No.1 slope break zone which is filled with hydrocarbon. The hydrocarbon properties differ greatly, and the oil-water interface is not horizontal but dipping northwestward. According to the geologic chromatographic effect, and the space distribution of the special compositions of natural gas and oil, it is indicated that the intersection zone of the northeast-striking faults and the northwest-striking No.1 slope break zone is the main pathway system that leads hydrocarbon into the No.1 slope break zone. Hydrocarbon was injected along the intersection zones and accumulated nearby, which resulted in the differences in compositions and properties of hydrocarbon.

2 Geologic setting

The Tarim Basin is representative of all the superimposed basins developed in west China. It has undergone complicated tectonic events in the Caledonian, Hercynian, Indosinian-Yanshan and Himalayan epochs. These tectonic events resulted in multi-cycle sedimentation and erosion, which formed multiple sets of regional unconformities in the basin. Multiple sets of reservoir-seal combinations were formed in the Ordovician, Silurian, Carboniferous and Tertiary strata (Jin and Wang, 2004; He et al, 2004; Pang et al, 2007). As one of the three uplifts in the Tarim Basin, the Tazhong Uplift lies in the middle of the central uplift zone and is surrounded by the Manjiaer Depression in the northeast, Awati Depression in the northwest and Tangguzibasi Depression in the southwest. The above three depressions are the potential source kitchens for the Tazhong area. All of these make the Tazhong Uplift a potential target for substantial hydrocarbon discovery (Fig. 1).

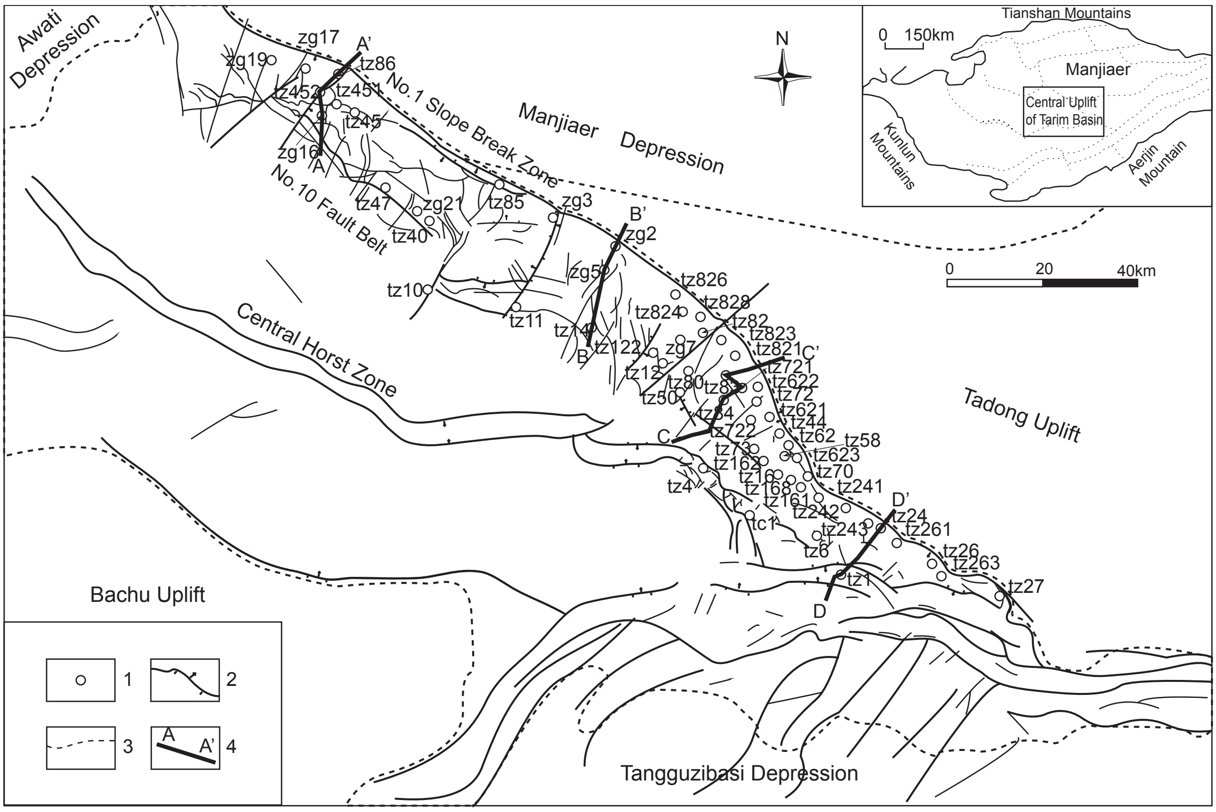

Fig. 1 Tectonic setting of the No.1 slope break zone in the Tazhong area

1 Well name; 2 Faults; 3 Tectonic dividing line; 4 Locations of the sections illustrated in Fig. 3

The deposits from Cambrian to Tertiary are more than 10,000 m thick (Fig. 2). As the regional cap rock in the Tazhong area, the shale of the Ordovician Sangtamu Formation is more than 1,000 m thick, while the thinner shales developed in the Silurian and Carboniferous form local cap rocks. Due to the effects of the regional and local cap rocks, there are multiple sets of reservoir-seal combinations vertically in the strata of Cambrian-Ordovician, Silurian and Carboniferous. Two sets of source rocks are found in the Tarim Basin, i.e., Cambrian–Lower Ordovician and middle-upper Ordovician source rocks, but the spatial distribution of each source rock and its contribution remain largely controversial (Xiao et al, 1996; 2000; Hanson et al, 2000; Sun et al, 2003; Zhang and Huang, 2005).

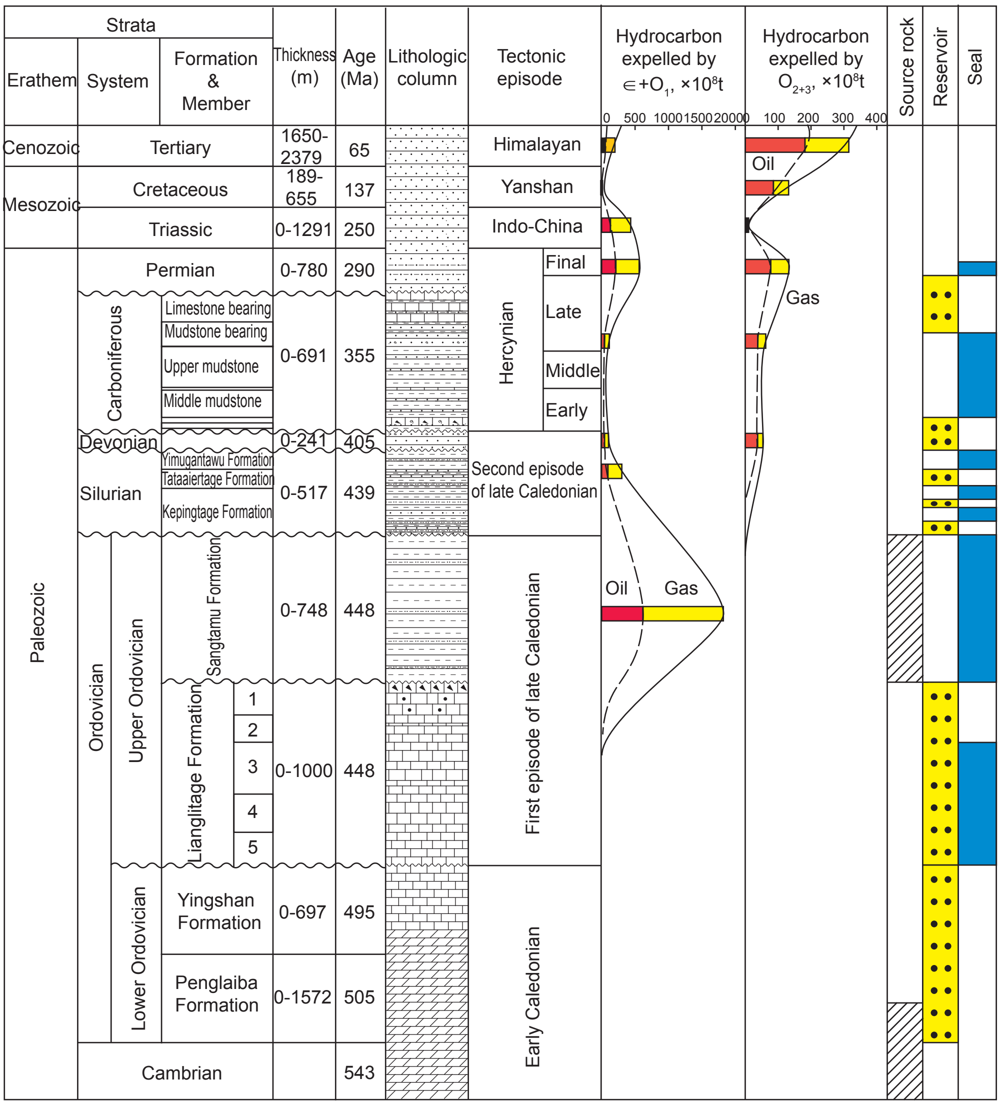

Fig. 2 Lithology and petroleum geologic settings in the Tazhong area

The No.1 slope break zone in the Tazhong area is a complicated structural belt, with 280 km in length, WNW trending, and an inverted "S" shape. It is the boundary between the Tazhong Uplift and the Manjiaer Depression (Fig. 1). The No.1 slope break zone formed its embryonic form in the late Yingshan period of the early Ordovician, reached its peak during the Lianglitage period of the late Ordovician, and formed its final shape in the late Sangtamu period of the late Ordovician. The No.1 slope break zone has been stable since the late Ordovician as shown in representative profiles (Fig. 3). The northeast-striking faults divided the early formed No.1 slope break zone into five segments (Wu et al, 2005), i.e., TZ24-TZ26, TZ62, TZ82, TZ54 and TZ45 from east to west with different structure types, which can be seen from the representative profiles from west to east (Fig. 3). The structures in the TZ45 well block are thrust faults developed mainly in the late Ordovician and are cut by the later northeast-striking faults. The structures developed in the TZ54 and TZ82 well blocks are detachment faults without obvious involvement of the basement as illustrated in the profile of BB'. The activity of the No.1 fault strengthened southeastward from the TZ82 well block. The structures developed in the east are complicated oblique thrust faults with obvious involvement of the basement. They also developed mainly in the late Ordovician with minor late-stage activities ever since then.

The five segments developed along the No.1 slope break zone correspond to the four main northeast strike-slip faults of TZ24, TZ82, ZG3 and TZ86, respectively (Fig. 1). The northeast striking faults were formed in the late Silurian according to the strata that were penetrated. The faults may have been reactivated during the Hercynian and Indosinian-Yanshan tectonic movements (Fig. 3, AA'). Only limited research has been done concerning the northeast striking faults since they were identified (Chen et al, 2008; Zhang et al, 2008).

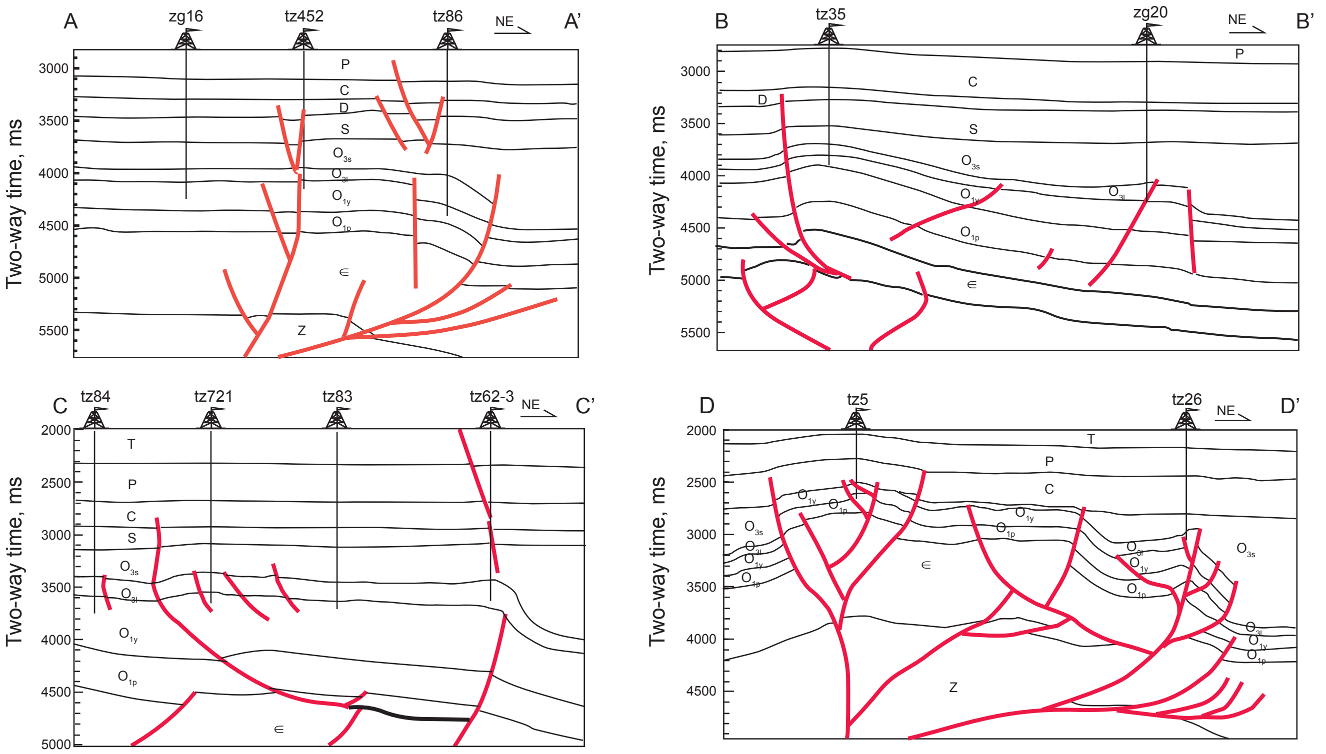

Fig. 3 Typical profiles illustrate the tectonic frameworks of different segments of the No.1 slope break zone. The profile AA', which is from the TZ45 well block, indicates basement involved thrusting and the intersected late-stage northeast striking faults. The profile BB', which is representative of the structure framework developed in both the TZ85 and the TZ54 well blocks, indicates detachment faults without obvious involvement of the basement. The profiles CC' and DD', which represent the gradual changing of the structure framework from the TZ62 well block to the TZ24 well block, indicate that tectonic movements strengthened southeastward from the detachment faults developed in the west to the complicated oblique thrust faults with obvious involvement of the basement in the east. All the profiles indicate a stable state for the No.1 slope break zone and an active state for the intersecting northeast striking faults since the late Ordovician.

Favorable reservoir belts of platform edge organic reef and grain bank facies are developed (Fig. 4) in the upper Ordovician strata in the Tazhong north slope zone, which is also the best area for hydrocarbon enrichment and exploration in the Ordovician carbonate (Wu et al, 2005; Wang et al, 2007; Han et al, 2008; Chen et al, 2008). The organic reef and grain bank facies of the Lianglitage Formation is the main reservoir in the No.1 slope break zone (Wang et al, 2007). The No.1 slope break zone was located on the platform edge during the middle-late Ordovician, and rimmed grain bank and organic reef systems were developed. Five sedimentary cycles occurred due to sea level fluctuation, and the overall thickness was about 100-300 m (Fig. 3). The second member of the Lianglitage Formation is the main production reservoir, and the sedimentary facies distribution is characterized by narrow framework reefs in the east and wide grain banks in the west. Four types of sedimentary facies are developed: organic reef, organic mound, grain bank and interbank sea (Fig. 4).

The carbonate reservoirs are complicated pore-fissure-fracture reservoirs mainly controlled by karstification and faulting. The capillary force developed between the pore-fissure-fracture system with high porosity and permeability and the surrounding wall rocks with low–ultra low porosity and permeability impeded the fluid exchanges of different pore-fracture units (Xiang et al, 2009), and created the relatively independent fracture-cave units (Wei and Kang, 2005; Guo et al, 2006) or formed fluid compartments, which have been recognized in the study of the pressure systems (Bradley and Powley, 1994; Zhu et al, 1997). This type of fracture-cave unit is characterized by pinch-and-swell structures in the seismic profile and forms key exploration targets.

3 Segmentation of hydrocarbon reservoir types and properties

Previous studies summarized the discovered reservoirs in the No.1 slope break zone as "gas in the east, oil in the west, and gas outside, oil inside" (Han et al, 2008). This reflects the overall hydrocarbon distribution characteristics, but one of

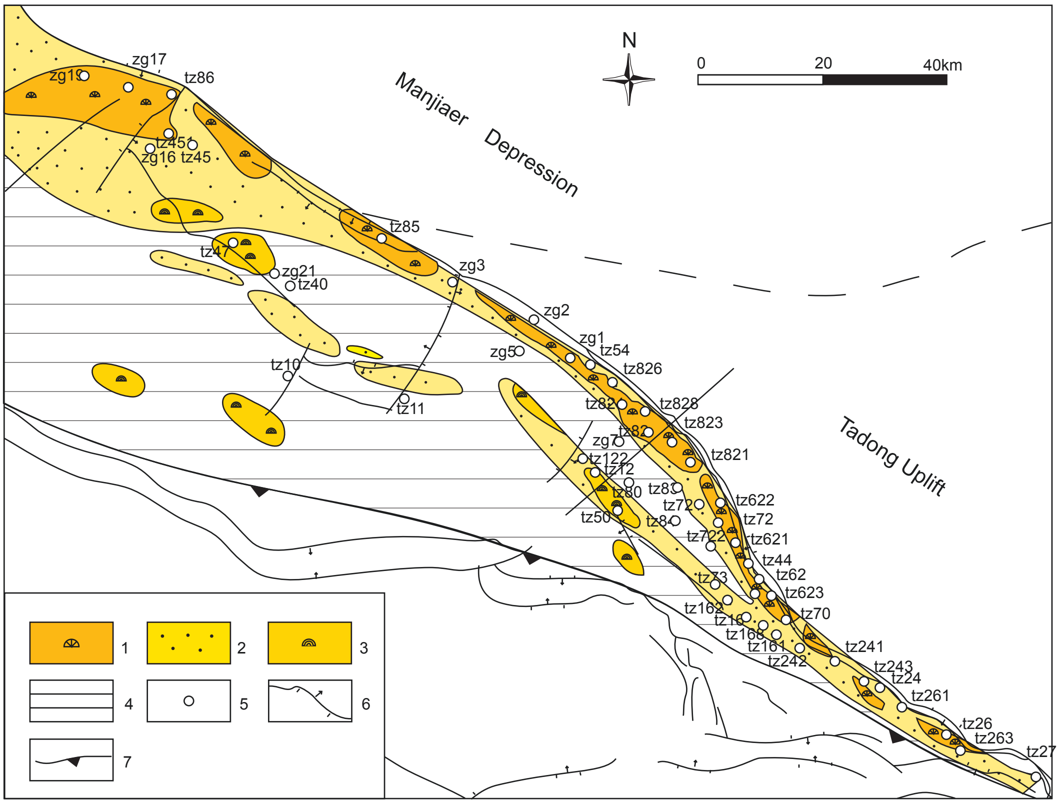

Fig. 4 Sedimentary facies distribution of platform edge organic reef and grain bank facies along the No.1 slope break zone
1 Platform edge organic reef; 2 Platform edge grain bank; 3 Grain bank in the platform; 4 Interbank sea; 5 Well; 6 Faults; 7 Strata pinch-out line

the most obvious characteristic is the E-W segmentation as shown in the following two aspects.

3.1 Segmentation of hydrocarbon reservoir types

The reservoirs found in the No.1 slope break zone are mainly condensate gas reservoirs and differ in different segments corresponding to the tectonic segmentation (Fig. 5). The reservoirs of different types appear alternately in the plane. They are condensate gas reservoir (TZ24 well block), condensate gas reservoir filled with small amounts of condensate oil (TZ26 well block), condensate oil reservoir (TZ82 well block), volatile oil reservoir (TZ85 well block) and condensate gas reservoir (TZ45 well block) in turn from east to west. Condensate gas reservoirs alternate with oil-bearing condensate gas reservoirs from east to west. This alternation corresponds to E-W segmentation of the overall tectonic framework in the Tazhong area (Fig. 1 and Fig. 3). The hydrocarbon productivity also alternates from east to west corresponding to the tectonic framework. Large amounts of hydrocarbon is produced from TZ45, TZ82, TZ62, TZ26 and TZ24 well blocks, all of which are the intersection zones between the northeast striking faults and the northwest striking No.1 slope break zone.

3.2 Segmentation of hydrocarbon properties

The natural gas in the No.1 slope break zone is dry gas with its gas ratio ($C_1/C_1–C_4$) generally greater than 0.95. The natural gas properties are characterized by segmentation (Fig. 5). The natural gas with N_2 content greater than 6% and less than 6% appear alternately in the lateral direction and the CO_2 content alternates between greater than 4% and less than 4%. The content of H_2S is also variable laterally. All the above characteristics indicate that the natural gas compositions have obvious W-E segmentation characteristics.

The crude oil is low-density (0.76-0.84 g/cm^3, averaged 0.81 g/cm^3), low-viscosity (1-10 mPa·s) condensate hydrocarbon as a whole, but the composition and properties are also characterized by segmentation like those of the natural gas (Table 1, Fig. 5). The crude oils with sulfur and colloid contents greater than 2% alternate with the oils with sulfur and colloid contents less than 2% (Table 1). Correspondingly, the saturated hydrocarbon and asphaltene contents also alternate from east to west. All the above characteristics indicate the segmentation of crude oil.

Table 1 Crude oil composition characteristics of different well blocks from east to west in the Tazhong No.1 slope break zone

Geochemistry parameters	TZ45	TZ85	TZ82	TZ62	TZ24-26
Colloid content, %	<2	>2	<2	>2	<2
Asphaltene content, %	<9	>9	<9	>9	<9
Wax content in crude oil, %	<5	>5	>5	>5	<5
Sulfur content in crude oil, %	<0.2	>0.2	<0.2	>0.2	<0.2
Saturated hydrocarbon content, ug/g	>80	<80	>80	<80	>80

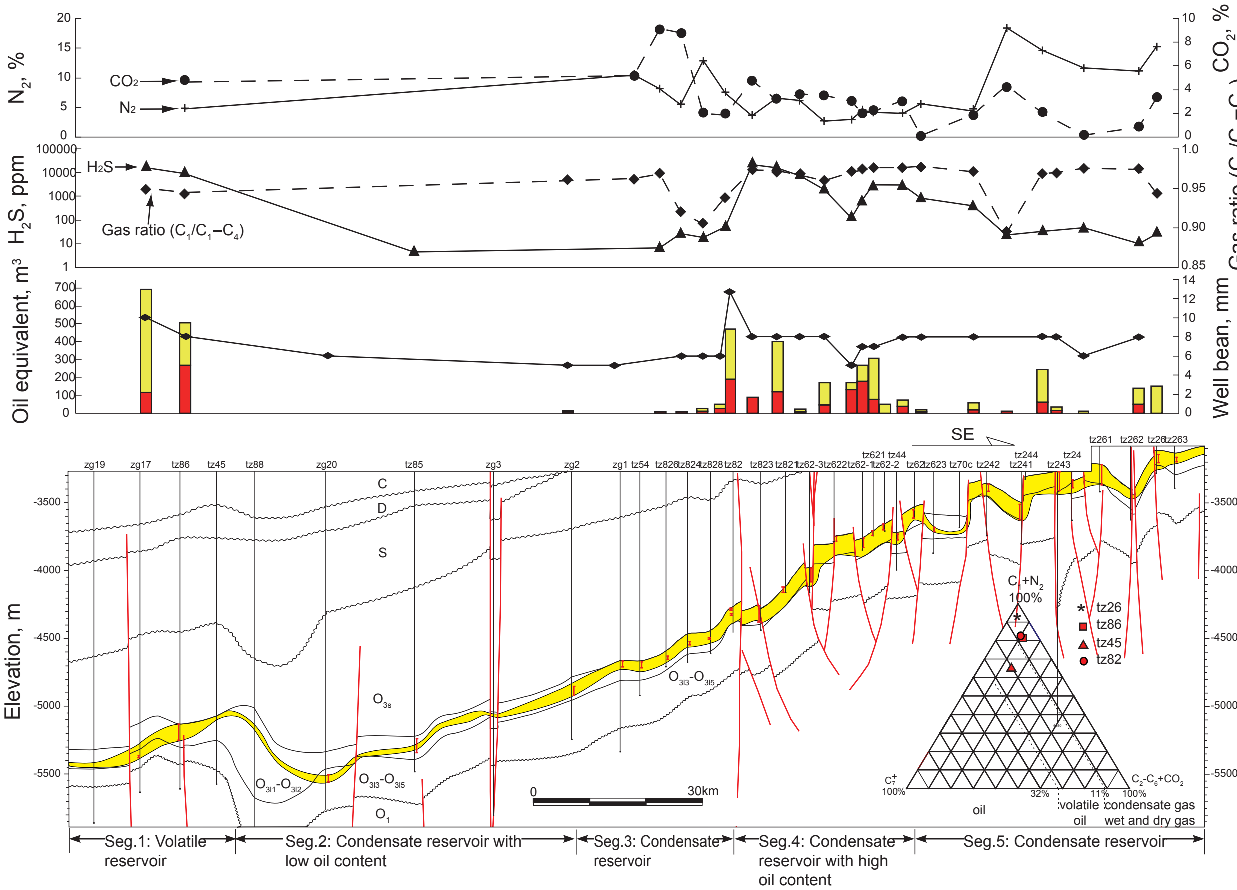

Fig. 5 Reservoir cross section along the No.1 slope break zone. The segmentation of the hydrocarbon characteristics is in accordance with the segmentation of the tectonic framework and the hydrocarbon reservoir types.

The above cut-off values are often the symbol of variations of crude oil properties according to the analysis of relationships between oil composition and its physical properties in the Tazhong area (Fig. 6). Colloid content in crude oil, normal crude oil and light crude oil can be divided at the 2% level. Besides, a saturated hydrocarbon content of 80 mg/L, an asphaltene content of 9% and a wax content of 5% can be the dividing point of normal crude oil and light crude oil. It can be inferred that the segmentation characteristics of crude oil in the Tazhong No.1 slope break zone are definite.

4 Hydrocarbon migration tracing

4.1 Geological background for tracing

The systematic and regular variations of hydrocarbon properties and composition contents can trace the hydrocarbon migration direction and indicate the main pathway systems if the hydrocarbons are sourced from the same source rocks according to the theory of geological chromatographic effect. The hydrocarbons found in the No.1 slope break zone were sourced from the mixture of the source rocks of the Cambrian–lower Ordovician and middle-upper Ordovician (Li et al, 2009).

The properties of the hydrocarbon discovered in the No.1 slope break zone have been determined by careful organic geochemical analysis. These indicate that the hydrocarbon with uniform middle-high maturity is sourced uniformly from the source rocks of Cambrian–lower Ordovician and middle-upper Ordovician (Li et al, 2008b). The parameters that indicate the high maturity of the hydrocarbon such as Ts/(Ts+Tm), TMNr, TeMNr are approximately equal to 0.5, >0.6, >0.6, respectively (Li et al, 2008b). This indicates that the crude oil is mainly of middle-high maturity.

The contents of methyl sterane, gamma napalite and tricyclic terpane are not very high, and the abundances of regular sterane, rearranged sterane and rearranged hopane with V-form are relatively high. It can be inferred that the source rock in this area is mainly middle-upper Ordovician according to the geochemistry index systems in the Tarim Basin (Xiao et al, 1996; 2000; Hanson et al, 2000; Sun et al, 2003; Zhang and Huang, 2005). All these parameters are almost uniform in the No.1 slope break zone and indicate a uniform hydrocarbon source. However, the monomer carbon isotope ratio of normal alkanes indicates that it originates from mixed source rocks, i.e., the typical middle-upper Ordovician (carbon isotope value is 34‰-35‰) and Cambrian–lower Ordovician (carbon isotope value is 29‰-30‰) source (Li et al, 2008b).

The main hydrocarbon migration and accumulation period is Himalayan, which is characterized by gas invasion (Wu et al, 2005; Han et al, 2008). The Tazhong area has experienced

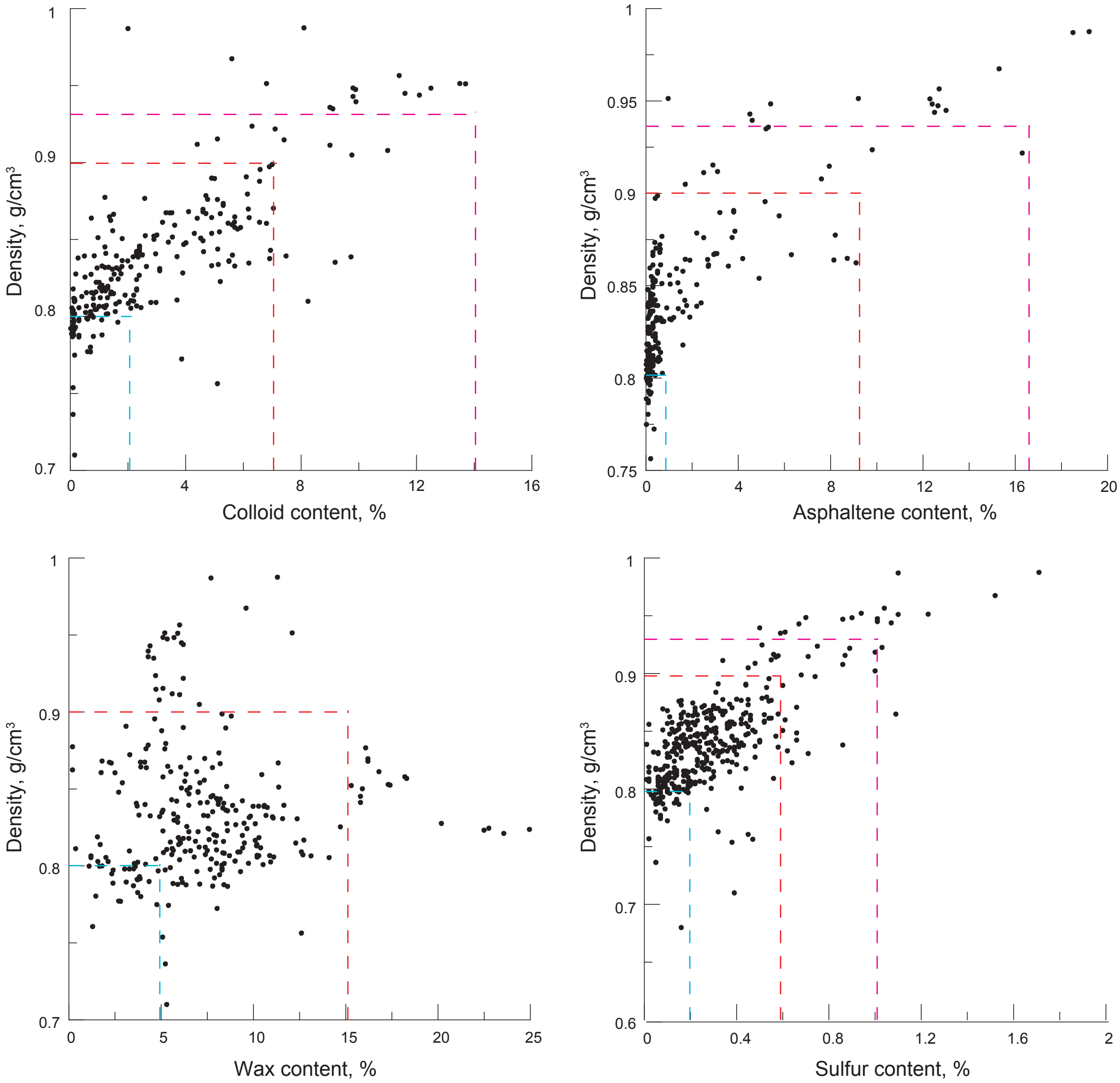

Fig. 6 Statistic analysis graphs of the relationship between physical properties and compositions of the crude oil in the Tazhong area. The rectangular areas define different types of crude oils mainly based on their density. We can read their compositions, which are the same as the segmentation values of the parameters shown in Table 1.

three periods of hydrocarbon accumulation, which correspond to middle Caledonian, Hercynian and Himalayan stages respectively (Wu et al, 2005; Xiao et al, 1996). The previous studies about the hydrocarbon composition, abundance and isotope of fluid inclusions have validated the characteristics of multi-phase hydrocarbon accumulation in the No.1 slope break zone. The hydrocarbon formed in the first two stages can only be identified from the fluid inclusions. The crude oil is mainly produced from the gas invasion during the Himalayan stage (Li et al, 2008a). This indicates that the hydrocarbon accumulation in the No.1 slope break zone is almost uniform.

The above characteristic makes it possible to study the hydrocarbon migration direction and the main pathway systems using geologic fractionation. The compositions and properties of crude oil and natural gas were analyzed to trace the hydrocarbon migration.

4.2 Oil properties and compositions

The crude oil varies in composition and properties systematically during migration due to geologic fractionation. The properties and compositions of the crude oil in the Tazhong No.1 slope break zone are characterized by obvious segmentation (Fig. 7-Fig. 9). There are significant anomalies in the intersection zone of the faults, especially at the side of TZ45 and TZ82, as shown by lower density (Fig. 7), higher viscosity (Fig. 8) and higher wax content (Fig. 9). The anomaly developed in the TZ24-TZ26 well block is divided into three parts, which can be related to the flower structure of strike slip faults as revealed by the seismic section.

The lateral variations of the properties and compositions allow the hydrocarbon migration direction to be determined. All the parameters are high at the intersection zone and decrease gradually with increasing distance. The above characteristic indicates that the intersection zone is the place

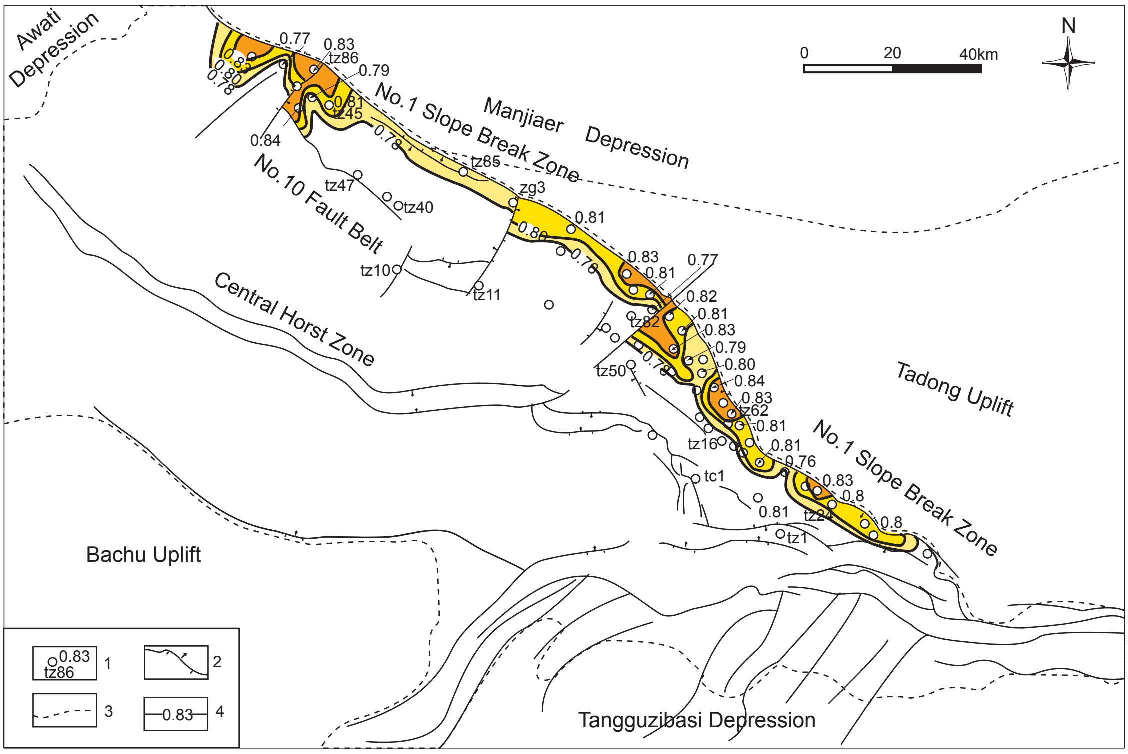

Fig. 7 Plane distribution of the oil density in the No.1 slope break zone in the Tazhong area
1 Oil density (g/cm³) in a well; 2 Faults; 3 Tectonic dividing line; 4 Contour of the density (g/cm³)

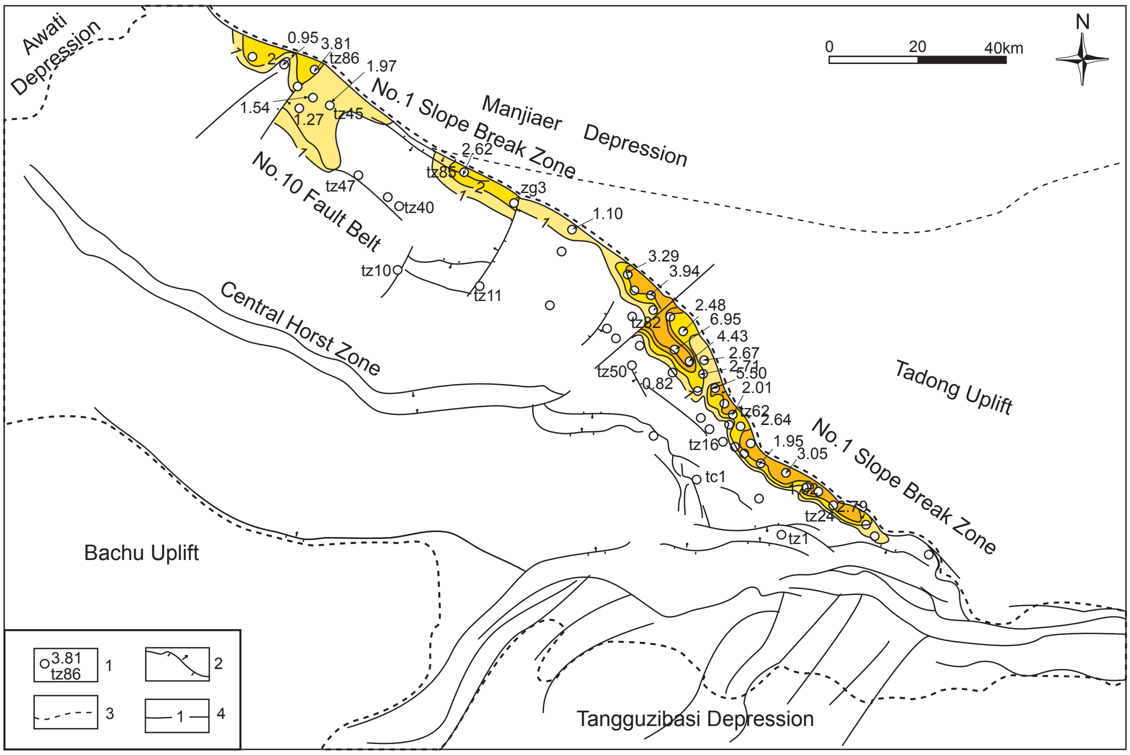

Fig. 8 Plane distribution of the oil viscosity in the No.1 slope break zone in the Tazhong area
1 Oil viscosity (mPa·s) in a well; 2 Faults; 3 Tectonic dividing line; 4 Contour of the viscosity (mPa·s)

where the hydrocarbon charges.

The anomalies of crude oil properties and compositions do not cover the overall T-shape area of the fault intersection zone, but appear on one side of the fault intersection zone, especially in the tectonic up-dip direction. Take the TZ82 well block as an example, the anomalies of the crude oil appear only in the tectonic up-dip direction of the TZ83 well block, while they are not obvious in the tectonic down-dip

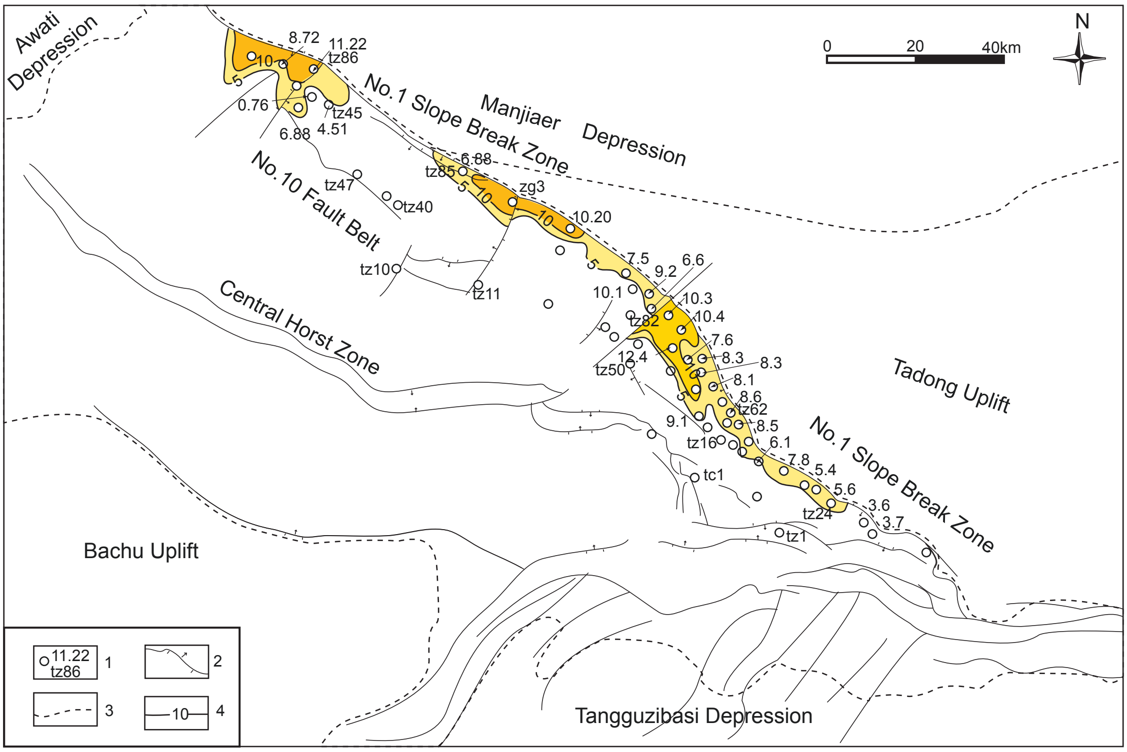

Fig. 9 Plane distribution of the wax content in the crude oil of the Tazhong No.1 slope break zone
1 Wax content (%) in a well; 2 Faults; 3 Tectonic dividing line; 4 Contour of the wax content (%)

direction of the TZ82 well block. These characteristics indicate that differential hydrocarbon migration and entrapment exists in different parts of the intersection blocks. Hydrocarbon is prone to be entrapped in the tectonic up-dip direction when charged from the intersection zone.

4.3 Gas properties and compositions

The natural gas varies in compositions and properties systematically during migration due to geologic chromatographic effect. The properties and compositions of natural gas follow the same variation rules as those of the crude oil. We take the plane distribution maps of gas/oil ratio (Fig. 10) and content of H_2S (Fig. 11) that represent natural gas injection intensity and hydrocarbon migration as an example. It is clear that the natural gas properties and compositions can be divided into five parts, each of which is similar to the segmentation of crude oil, and matches well with the tectonic framework of the No.1 slope break zone.

All the parameters show high anomalies at the fault intersection position of NE-striking faults and the No.1 slope break zone. The gas/oil ratio is 4-5 times higher and the content of H_2S is three orders of magnitude higher at the intersection zone. Both of them decrease away from the fault intersection zone and can be treated as the effect of hydrocarbon migration. The above facts again indicate that the late stage gas charging is along the fault intersection zone.

Controlled by the complicated pore-fissure reservoirs, hydrocarbon charged from the intersection zone will first occupy the pore-fissure systems nearby, and then spread away from the charging position. This will result in the high gas/oil ratio, abnormally high gas ratio (C_1/C_1–C_4) and high concentration of H_2S near the fault intersection zones, and make the crude oil have lower density, higher viscosity and higher wax content. The above anomalies will gradually disappear with increasing distances away from the fault intersection position.

Analogous to the distribution of oil properties and compositions, the anomalies of the natural gas do not cover the overall T-shape area of the fault intersection zone. They are only shown in the tectonic up-dip direction as shown in the TZ82 well block. This characteristic again indicates that differential hydrocarbon migration and enrichment has occurred in different parts of the intersection zone.

5 Discussion

5.1 Hydrocarbon charging along the fault intersection zone

5.1.1 Theoretical support

There is significant theoretical support for hydrocarbon charging along limited pathway systems. Hydrocarbon migration from source rock to the trap can be divided into three different stages. First, hydrocarbon migrates and accumulates to the top of the conductive layer under the drive of buoyancy. Then hydrocarbon migrates toward the structural ridge along the conductive layers. Finally hydrocarbon migrates along the main pathway systems, which are controlled by the shape of the carrier bed (Hunt, 1994), especially all kinds of structural ridges like the nose structure (England et al, 1987; Hindle, 1997). The hydrocarbon generated at late stage is prone to migrate along the early formed pathway systems (Thompson,

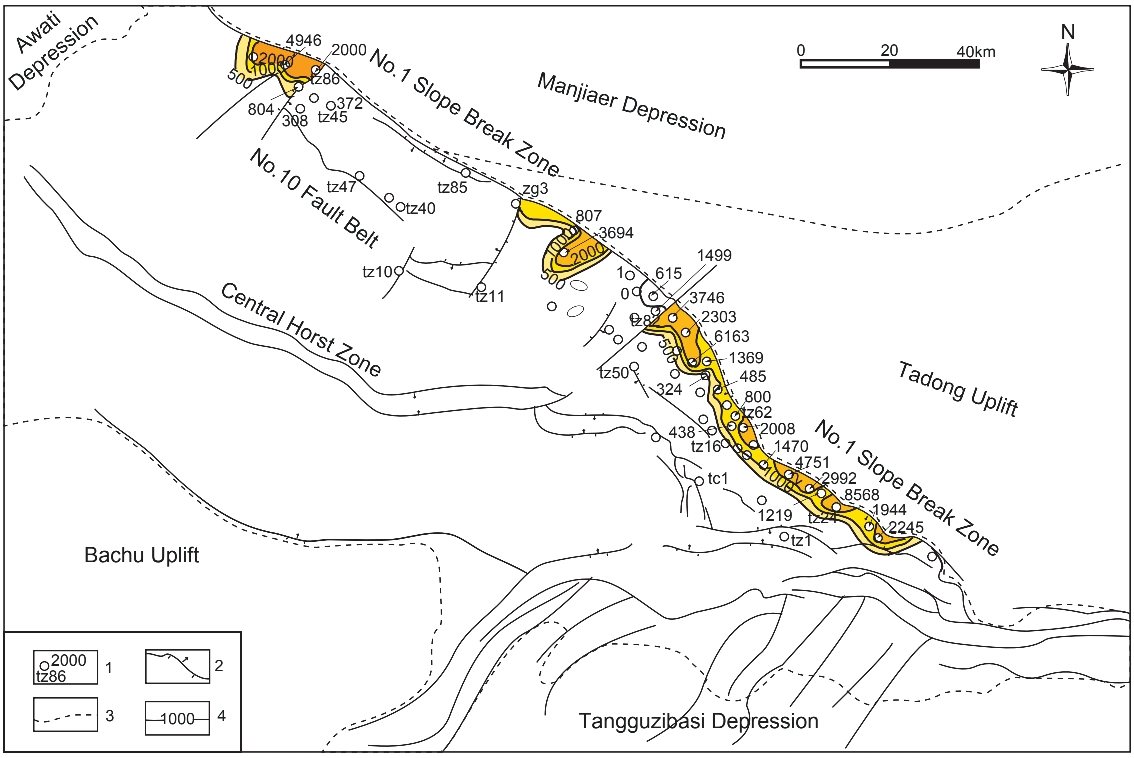

Fig. 10 Plane distribution of the gas/oil ratio in the Tazhong No.1 slope break zone
1 Gas/oil ratio in a well; 2 Faults; 3 Tectonic dividing line; 4 Contour of gas/oil ratio

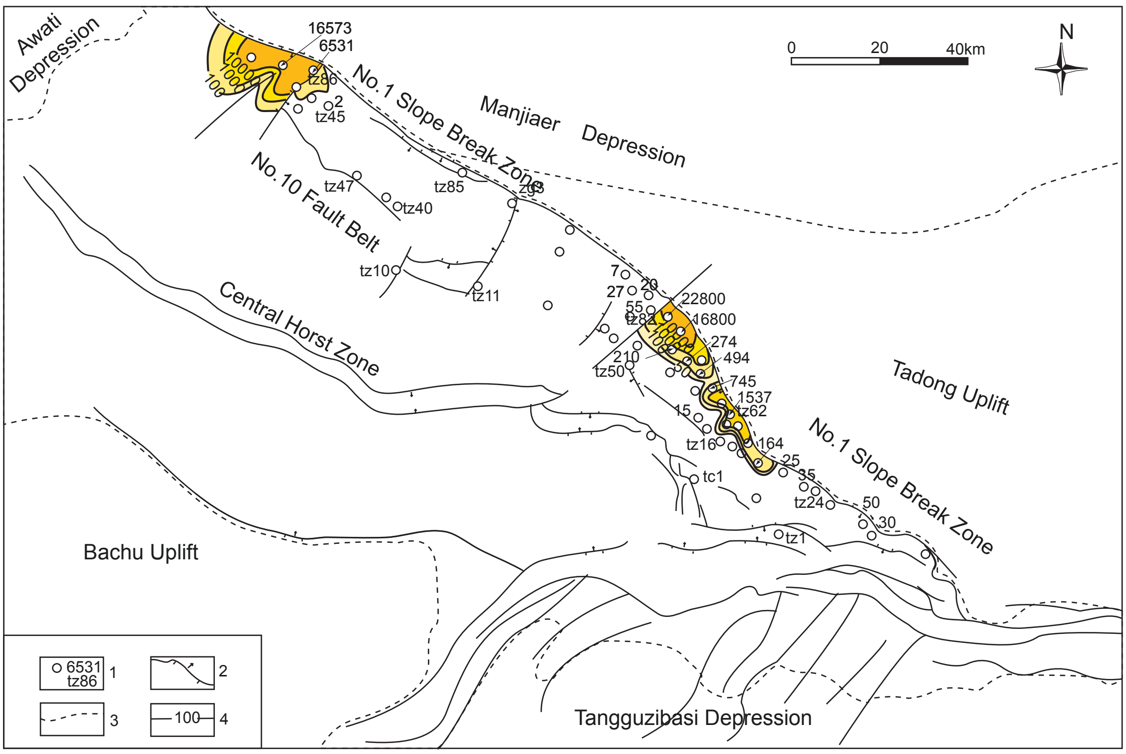

Fig. 11 Plane distribution of H_2S content in the natural gas in the Tazhong No.1 slope break zone
1 H_2S content (ppm) in a well; 2 Faults; 3 Tectonic dividing line; 4 Contour of the H_2S content (ppm)

1991). Secondary hydrocarbon migration does not use all the carrier beds, but it follows limited carrier beds with better physical properties. In the case of the sandstone conductive layer, the thickness is less than 6 m (Miles, 1990).

Controlled by the above mentioned mechanisms, hydrocarbon tends to charge traps that are far from the source kitchen. These processes have been shown by the typical hydrocarbon migration model in Fig. 6 (Hindle, 1997).

Hydrocarbon is prone to charge a trap in the form of a point or line, rather than a plane. This effect becomes obvious for a trap that is far away from the source kitchen.

The Tazhong area is far away from its main hydrocarbon-generating depression—the Manjiaer Depression, with a distance of 20-40 km. The hydrocarbon first migrates from the source kitchen to the nearby structural ridge, then migrates to the traps in the Tazhong area along the main pathway systems, which forms a point charge to all the traps developed in the Tazhong area. This kind of charging is more effective by reducing the hydrocarbon loss due to absorption on its migration way compared with the traditional idea that the hydrocarbon charges along the whole fault plane of the No.1 slope break zone (Han et al, 2008; Wu et al, 2005). All the geochemical indexes in the Tazhong area prove that hydrocarbon charges from the intersection zone of NE striking faults and the No.1 fault, which results in the segmentation and the local anomalies.

5.1.2 Improvement of physical properties

The plane distribution of the permeability indicates that faulting improves the physical properties of the reservoir greatly and forms better hydrocarbon migration pathway systems. The reservoir is controlled by the primary sedimentary environment and the late-stage diagenesis, especially the karstification (Zhou et al, 2008; Liu et al, 2008). Although the No.1 slope break zone is in good sedimentary facies of framework reefs and grain banks, the reservoir has low or ultra-low porosity and permeability, with the porosity<5% and permeability<1 md as shown in Fig. 8.

Faults can significantly improve the physical properties of reservoirs. The porosity and permeability relationship (Fig. 12) indicates that the pore structure can be classified into three types, which are porous, fractured and fractured-porous respectively (Liu et al, 2008). The above three types of pore structure are related to the original sedimentary facies, tectonic activities and their combined effects respectively. The reservoirs near the fault intersection zone are mainly fractured, but those away from the intersection zone are mainly porous, according to the comprehensive analysis of porosity-permeability relationship from the exploration wells (Fig. 3). The permeability of the reservoir near the fault intersection zone is 1-2 orders of magnitude higher than that away from the intersection zone. However, the level of change declines away from the intersection zone. This illustrates that the fault intersection zone is prone to form fractured reservoirs, which greatly influences the lateral and vertical hydrocarbon migration.

5.1.3 Localized and repeated strain controls the fault activity

Another reason that makes the physical properties better near the fault intersection zone is that it is the centralized position of stress and strain, which is favorable for repeated

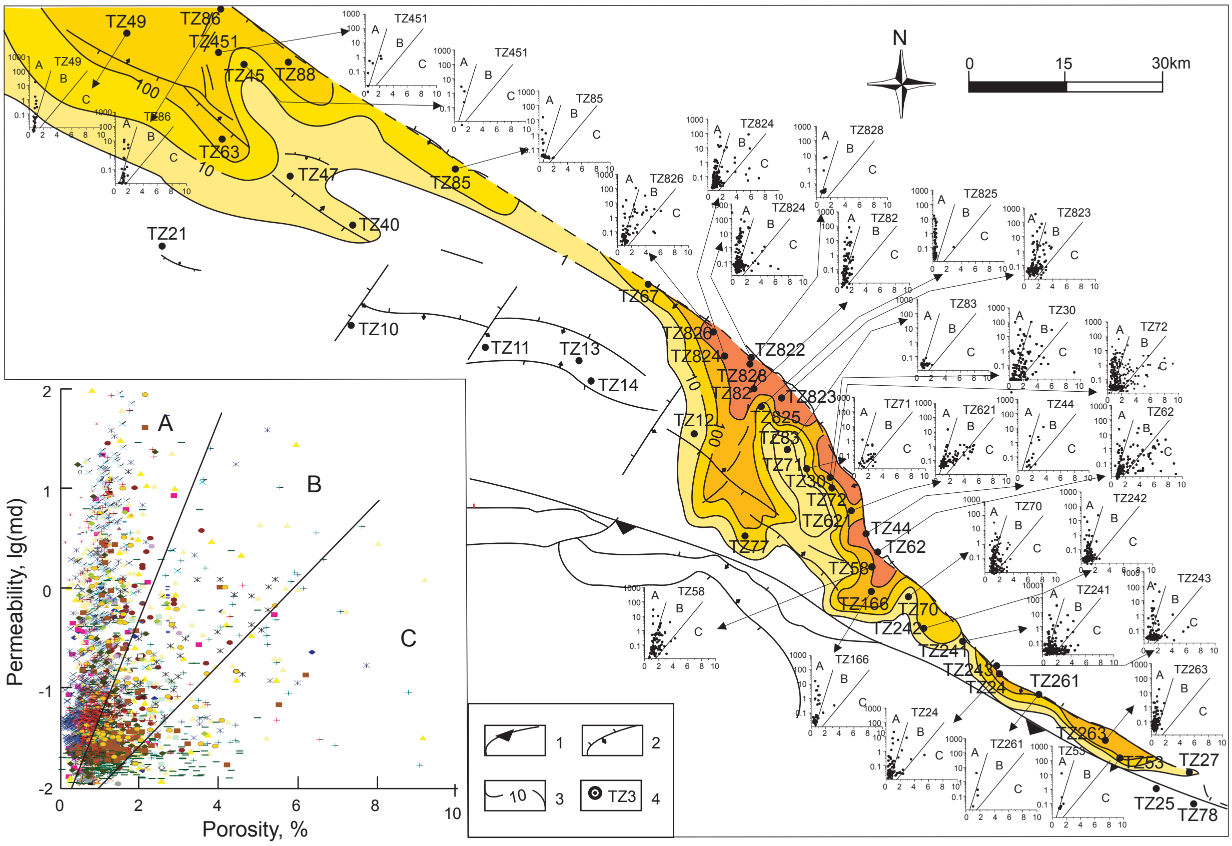

Fig. 12 Plane distribution of reservoir porosity and permeability in the No.1 slope break zone

A: Fissure-fracture controlled reservoir with high permeability and low porosity; C: Porosity controlled reservoir with high porosity and low permeability, mostly controlled by the original sedimentary facies; B: Porosity-fissure controlled reservoir with both porosity and permeability between A and C. The reservoir changed into type A at the intersection zone and the permeability increased by two orders of magnitude compared with that far away from the intersection zone. 1 Denudation pinch-out line; 2 Faults; 3 Permeability (md); 4 Well location and name fracturing during multi-stage tectonic movements. According to the rock mechanics, the rock mechanical strength near the fault intersection zone is lower and the fault can be more easily reactivated compared with the wall rock even under the same conditions of tectonic stress and fluid pressure. As a result, vertical hydrocarbon migration systems can be formed easily. The research results from Wu et al (2004) indicate that the intersection zone shows higher thermal infrared radiation (De Loor, 1969; Gachkevich et al, 2002) under cyclic compressional and tensional stress. The results clearly show that the intersection zone tends to fracture. The Tarim Basin has undergone multi-stage tectonic movements since Cambrian as shown by the unconformities in Fig. 2. Different kinds of fractures formed at different stages of tectonic movements can be identified from drill core. High-angle extensional fractures formed in the Caledonian–early Hercynian are of significance for improving the physical properties of the reservoir, while late-stage conjugate fracture is of limited significance (Wu et al, 1999). The physical properties near the intersection zone are not controlled by the evolution of the No.1 slope break zone, but by the intersection faults.

5.1.4 Formation mechanisms of the fault intersection

Multi-stage tectonic movements in the superimposed basins contribute to the intersection of the faults formed simultaneously or faults formed at different stages of tectonic movements. The fault intersection has the following mechanisms. 1) Conjugate faults: two groups of faults that formed in the same period under the same stress field. 2) Transform fault: a horizontal fault that has larger strike slip motion component. Normal fault and extensional tectonic system terminate in the strike slip fault, and the strike slip fault spreads the deformation between normal faults and extensional structures (Morley, 2002). 3) Faults that formed at different stages under different stress fields. The No.1 slope break zone was formed at the middle Caledonian and has been almost stable ever since then (Fig. 3). However, the corresponding NE striking faults were formed in the late Caledonian. Strong tectonic tilting occurred in the northeast direction in the Tazhong area controlled by the subduction and extinction of the Arkin Ocean during the late Caledonian stage. Due to this tectonic movement, the structural high, which originally lay in the TZ45 well block, migrated gradually southeastward to the TZ1 well block. The tectonic framework of the Tazhong area is formed and characterized by zonation in the north-south direction and segmentation in the west-east direction. The cross-cutting faults developed in the TZ82, TZ45 and ZG3 well blocks were all formed in response to the tectonic movement.

5.2 Differential hydrocarbon migration and accumulation

The hydrocarbon productivity (Fig. 5) and quality (Fig. 6-Fig. 11) all indicate differential hydrocarbon accumulation between the hanging wall and the footwall of the northeast striking faults. The productivity at the hanging wall is high and the physical properties are better. Taking the TZ82 and TZ83 well blocks as an example, the hydrocarbon productivity is high at the TZ83 well block (Fig. 5) as a whole, while only one well in the TZ82 well block obtains high oil productivity. All the parameters are divided into two parts by the northeast trending faults. The parameters on the southeast side are one to two orders of magnitude higher than those on the other side.

The above characteristics indicate that differential hydrocarbon migration and accumulation mechanisms existed at different parts of the faulted block. This is due to different types of fault breccia developed during faulting. Fault breccias can be generally divided into three types according to the research by Aydin (2000): deformation bands or shear bands in porous rock formed by localization of shearing and volumetric strain (Fig. 13(a)), faults formed by shearing along joints or joint zones (Fig. 13(b)) and fault breccia associated with dilation by pull-apart zones (Fig. 13(c)). Due to the common feature of two to four orders of magnitude reduction in permeability of deformation bands in the first and second cases, the hydrocarbon charging point determines how the hydrocarbon migrates and where it accumulates. For example, if the hydrocarbons charge from the left side, they will accumulate in the left side instead of the right side, resulting in the dividing effect illustrated previously by the parameters of the oil and gas. Also due to the two to four orders of magnitude increase in permeability of deformation bands in the third case, hydrocarbons can migrate vertically and accumulate in the up-dip area of the faulted blocks. Contrary to the former two cases, all the components and parameters are distributed smoothly across the faulted zone and will not result in the dividing effect.

The plane distribution of the physical properties indicates that the internal structure of the northeast striking fault may be similar to the second case. The distribution of the permeability and porosity is as a whole divided into a number of parts by the northeast striking faults (Fig. 12). The permeability and porosity are low at the core of the deformation bands, while being one to four orders of magnitude higher on both sides.

The internal structure of the fault developed along the No.1 slope break zone may be similar to either the first or the second case. Although some parts are in the same depositional facies of organic reef or grain banks, their physical properties are one to two orders of magnitude different. These characteristics exclude the dominant control from the depositional facies. It is hard to distinguish those formed by the No.1 slope break zone and those formed by the northeast striking faults. The main sediments in contact with the Lianglitage Formation are the thick mudstones of the Sangtamu Formation, which are the main regional cap rocks to the reservoir. Taking the depositional setting into consideration, we suggest that the internal structure is similar to the first case. It will hinder the cross migration of the hydrocarbon from the Manjiaer Depression to the No.1 slope break zone. The above deduction again supports the conclusion that hydrocarbons charge from the intersection zones.

5.3 Implication for hydrocarbon exploration

Hydrocarbons charging from the intersection zone of two different striking faults and accumulating in the traps nearby

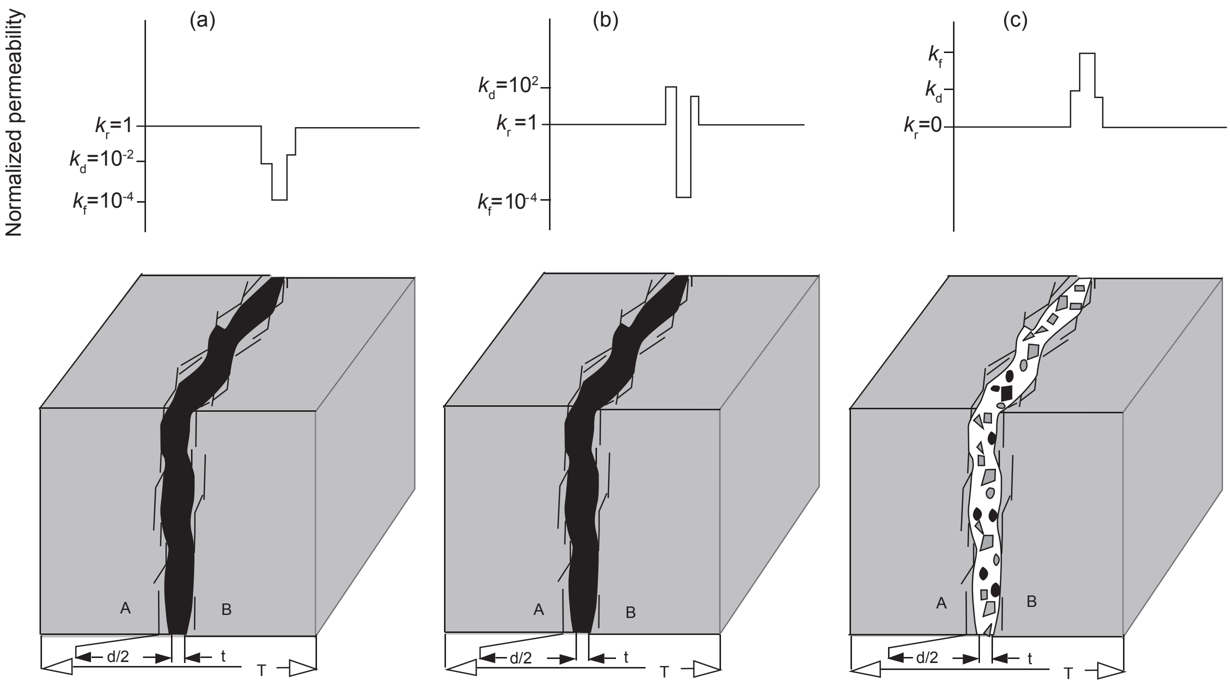

Fig. 13 Permeability structures of fault belts and corresponding differential migration and accumulation effects (Aydin, 2000). (a) A deformation-band fault zone with reduced permeability (k_f) in a direction perpendicular to the fault. The degree of permeability reduction depends on the lithology of the rock but on average the reduction is two to four orders of magnitude with respect to that of the rock matrix. (b) A fault developed by shearing across a joint zone. Fault rock formed by this process is similar to that of the deformation band process but it is surrounded by a damage zone, more permeable than the parent rock. (c) A brecciated fault zone filled with hydrocarbon. The permeability (k_f) depends on the porosity of the zone and the ratio of the fault thickness to particle radius.

suggest that the hydrocarbon exploration of a fault system should first begin at fault intersection zones. The hydrocarbon charging point and the nearby block zones which define the exploration play and further study of the migration and distribution processes in different parts of the faulted blocks will guide the choice of exploration targets.

The strike faults are characterized by a near vertical main fault, branching upward gradually, and with a flower structure. These structural characteristics result in the redistribution of the hydrocarbon in different blocks of the flower structure along its upward migration path.

The degree of completeness of the flower structure developed in the strike slip fault has positive correlation with the improvement of the reservoir properties and also with the hydrocarbon abundance. The strike slip fault in the TZ24-TZ26 well block is a complicated flower structure, while the faults in the ZG3 well block are two simple vertical faults without a flower structure. The plane distribution of the physical properties of the reservoir (Fig. 12) indicates a two to four orders of magnitude improvement in the TZ24-TZ26 well block, while no obvious improvement (one order at most) in the physical properties of the ZG3 well block (Fig. 12).

The hydrocarbon enrichment is positively related to the complexity of the internal structure of the strike slip faults. Abundant hydrocarbon resources have been found in the TZ24-TZ26 well block with gas proven reserves of 1.42×10^9 m^3 and condensate oil proven reserves of 8.9×10^6 tons. In contrast, geological reserves have not been determined in the ZG3 well block although abundant hydrocarbons are found.

6 Conclusions

1) The Tazhong No.1 slope break zone is divided into five parts from east to west by the intersection of northeast striking faults. Correspondingly, the types of the oil reservoirs, hydrocarbon properties and compositions are also divided into five parts from east to west.

2) Hydrocarbons charged from the intersection zone of two different striking faults, resulting in the anomalies of hydrocarbon properties and compositions at the intersection zone. The anomalies tend to vary systematically and weaken along the up-dip structure from the intersection zone.

3) Hydrocarbon charging from the intersection zone of different striking faults accords with the theory of main hydrocarbon migration pathway systems and improves the efficiency of hydrocarbon migration and accumulation. Multi-stage tectonic movements in the superimposed basins have resulted in the intersection of different striking faults formed simultaneously or at different periods. The intersection zones of the faults could easily result in the concentration of stress and strain. As a result, the porosity and permeability near the intersection zone are two to four orders of magnitude higher, which forms the main hydrocarbon migration pathway systems.

4) Different types of internal fault structures have resulted in differential hydrocarbon migration and accumulation. The hydrocarbon charging point determines how the hydrocarbons migrate and where they accumulate. If deformation bands exist, they will hinder the cross fault migration due to the common feature of two to four orders of magnitude reduction

in permeability. Otherwise, hydrocarbons tend to accumulate in the up-dip structure under the control of buoyancy. The hydrocarbon charging points define the exploration plays and the hydrocarbon distribution along the flower structure of the strike slip faults determines the exploration targets.

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