Effect of Thrust Structural Pattern on Carbonate Reservoir and Gas Reservoir Type in the East of Amu Darya Right Bank

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Abstract: The Amu Darya Right Bank is located in the northern part of Turkmenistan. Middle-Lower Jurassic coal-bearing deposits, Middle-Upper Jurassic carbonate rocks and Upper Jurassic salt rocks are the major sedimentary assemblages. The east of the right bank is located in the Southwestern Gissar thrust belt, and the reservoir is the most important risk factor. Based on the fault-related folds theory, have analyzed the structural pattern of the thrust - fold belt, figured out their effects on development of fractures and carbonate reservoirs, and influence on natural gas accumulation. The study shows that breakthrough fault-propagation folds and fault-bend folds dominate the east. With structural highs far away from the primary fault, breakthrough fault-propagation folds have abundant fractures, but weak dissolution, where the reservoirs and gas pools are mostly fracture-pore type, the wells have low production, and the water/gas ratio increases with the increase of distance from the primary fault. Fault-bend folds have structural highs close to the primary fault, abundant fractures, and strong dissolution by deep hydrothermal fluid, so the reservoirs and gas pools in them are mostly fracture-cave type, with high production of well. After comprehensive analysis, it is suggested to adopt deviated wells on breakthrough fault-propagation folds, and vertical wells on structural highs of fault-bend folds.

1 INTRODUCTION

Amu Darya is a large-scale petroliferous basin in Central Asia, with resources of 3.308×10^9t, of which over 98% is natural gas (Yu et al., 2015). In recent years, Gunorta Eloten, the world's second largest gas field was discovered in the Callovian-Oxfordian carbonate rock in the pre-salt Jurassic assemblage, which is estimated to have geological reserves of 7 trillion cubic meters (Zhang et al., 2010). The Amu Darya Right Bank is located in the northeast of the basin. The east of the Right Bank with thrust structures, as well as a potential play that may provide the possibility of rapid increase in reserves. The reservoir condition is the primary geological risk. Therefore, studying the reservoir and the hydrocarbon distribution law of the thrust structural belt is necessary, which will provide a guidance to future planning of exploration wells (Mu, 2017).

In China, many researchers have studied the fracture distribution law and hydrocarbon accumulation law of the thrust structural belts in the Tarim, Junggar and Tuha basins, with the emphasis placed on control of fault system over reservoir and hydrocarbon distribution (Jin, 2012;Wang, 2015;Shi et al., 2005;Neng et al., 2017). Tang Ying et al. (2016) examined the influence of tectonic activity on carbonate rock formation, fracture distribution and hydrothermal flow activity in the Zagros Foreland Basin (Tang et al., 2016). Many researchers have looked into the development characteristics of the carbonate reservoir deposited in the Amu Darya Right Bank from the perspectives of reservoir sedimentation and diagenesis (Zhao,

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2011;Liu et al., 2012). They all reached the conclusion that sedimentation and diagenesis controlled on formation of the Callovian-Oxfordian carbonate reservoir, and dissolution and fracturing were major factors accounting for the improvement and enhancement in reservoir performance. Some researchers pointed out that, in the east of the block the presence of structural fractures enhanced physical properties of carbonate reservoir, and the fracture-cave systems adjacent to faults are favorable places for hydrocarbon accumulation (Nie et al., 2013).

Based on previous studies, the thrust fault-related fold patterns and the types of the Callovian-Oxfordian carbonate reservoirs and gas pools are linked together in this study. Firstly, guided by thrust fault-related fold theory (Shaw et al., 2008), the fault features and structural styles have been analyzed. And then through the research of distribution of fracture in different structural styles in the outcrop of study area and drilling core data, the thin section, fluid inclusions, to find out the influences of different thrust structural patterns on the natural gas accumulation and the types of gas pools formed. Finally, the suggestion of the well trajectory in different structural styles was proposed.

2 REGIONAL GEOLOGIC SETTING

The Amu Darya Basin is situated within the Tethyan tectonic domain, in the Karakum plate, and was separated from the Tarim plate due to the Cenozoic Alpine new tectonic movement (i.e., the Himalayan movement) (Luo et al., 2005). The basin is bordered to the north by the Qizilqum mountain, to the south by the Kopet-Dag mountain, to the east by the Gissar Range, and to the west by the Central Karakum Arch(Figure 1). It is a Meso-Cenozoic foreland basin formed on a Permian-Triassic rift and has gone through three major stages: the Permian-Triassic rifting, Jurassic-Paleogene depression and Neogene compression (Natal'In et al., 2005;Golonka, 2004).

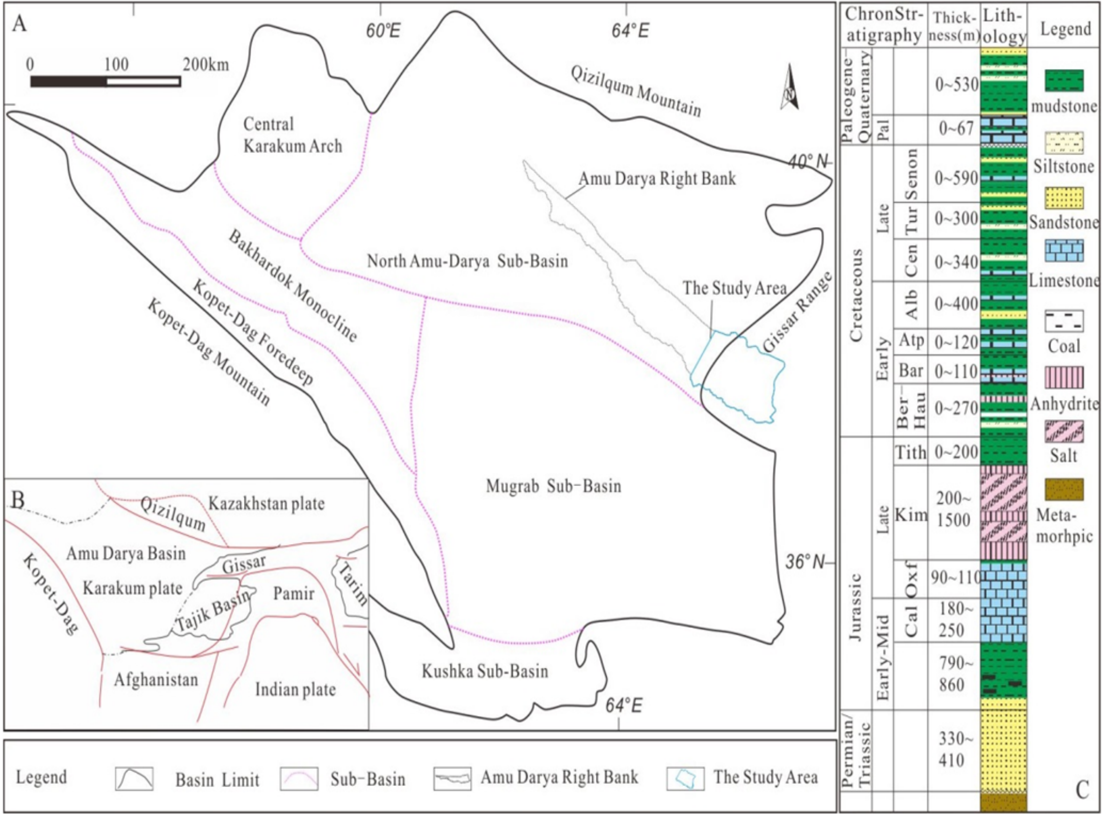

Figure 1: (A)Location map of the study area. (B)The tectonic unit map of Amu Darya Basin. (C)Stratigraphic chart for the study area (Modify from Ulmishek G F (Ulmishek, 2004), 2004 and Thomas J,1999 (Thomas et al., 1999)).

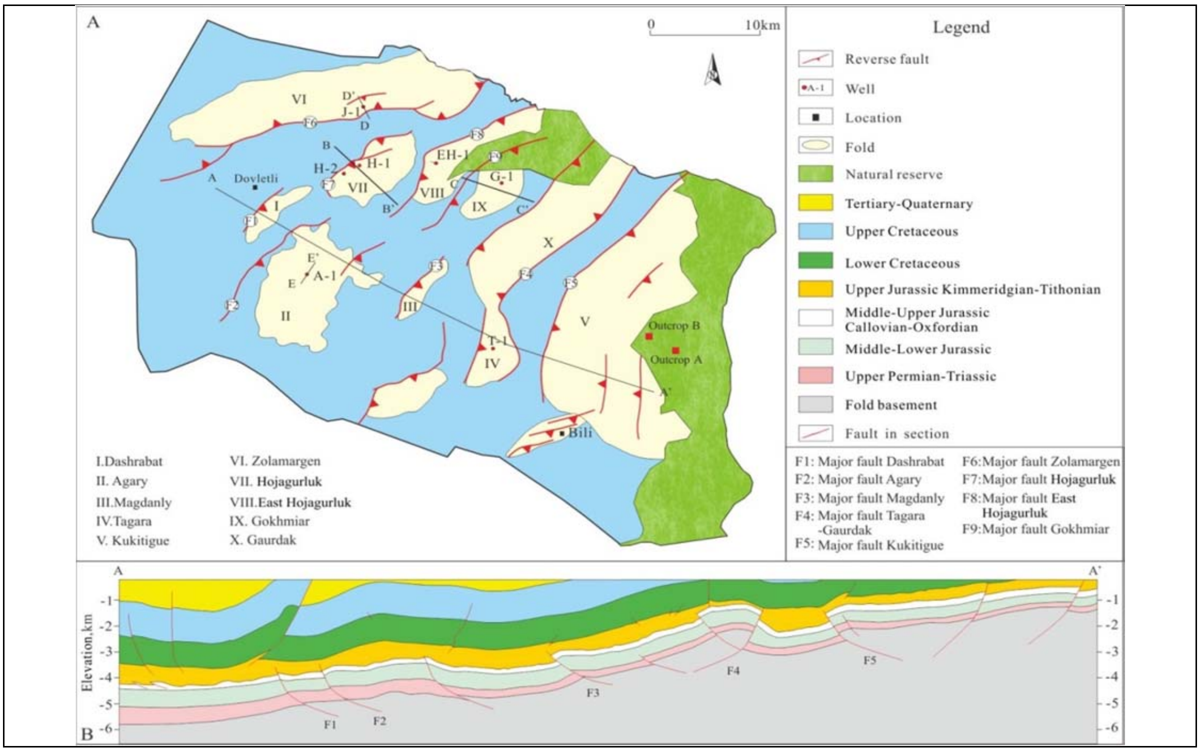

Figure 2: (A)Major geological structures (faults, folds) of the Callovian-Oxfordian carbonate. (B) C geological cross-section showing the structural framework. For position see the map A.

The eastern of the Amu Darya Right Bank is located in the northeastern part of the basin, covering the Gissar Range and its piedmont. From the Permian to Triassic, the Paleo-Tethys Ocean expanded and the study area was under an extensional environment, which enabled formation of a 400 m thick sandstone-dominated transitional stratum. Since the Jurassic, the stable depression sedimentation period begun, allowing for deposition of the Middle-Lower Jurassic coal-bearing clastic rock(thickness 790-860m), Callovian-Oxfordian carbonate rock(thickness 270-360m), Kimmeridgian-Tithonian salt-gypsum rock(thickness 200-1500), Cretaceous marine clastic and carbonate rocks(thickness 560-2100m), and the Paleogene clastic rock(thickness 0-600m), with the maximum thickness of 5000 m(Figure 1). As a result of the collision between the Indian and Eurasian plates during Neogene, the Pamirs Plateau and Gissar Range was uplifted. And the east of study area eroded (Figure 2-B).

The Middle-Lower Jurassic coal-bearing clastic rock, Callovian-Oxfordian carbonate rock and Kimmeridgian salt-gypsum rock constitute a high-quality source-reservoir-cap assemblage, with the pre-salt Callovian-Oxfordian carbonate rock being the primary target layer for exploration. By comparing the thermal history of the source rock in the Murgab sub-basin with the burial and thermal history of the central part of the Amu Darya Right Bank (Nie et al., 2017), it is found that in the study area, the common burial depth of the source rocks in the lower section of the Middle-Lower Jurassic strata reached up to 4000 m towards the end of the Paleogene, with the ancient formation temperature of about 120℃, indicating the source rocks had entered the peak hydrocarbon generation stage. During Neogene, the east of the East Hojagurluk-Tagara uplifted greatly and the Middle-Lower Jurassic source rocks uplifted to a depth of less than 2200 m; and to the west, source rocks in the piedmont area were further buried to a depth of 4500 to 5000 m, with formation temperature exceeding 160℃, and some areas entered the condensate-wet gas stage (Fang et al., 2014). By Comparing the well H-2 and T-1, in the east of the study area the maximum burial depth of the carbonate rock ranged from 3000 to 3500 m, in the west 3500 to 4000 m

(Li, 2015). In the east actual measured formation temperature of well G-1 in the Callovian-Oxfordian carbonate rock is only 60°C, and in the west from 110 to 130°C of the wells A-1, H-2 and J-1.

3 FAULT FEATURES AND STRUCTURAL STYLE

The study area consists of pre-salt and post-salt structural systems, divided by the salt-gypsum rock bed. This study targeted the pre-salt thrust system formed as a result of the collision between the Indian and Eurasian plates.

3.1 Fault Features

Profile shows that, faults in the pre-salt structure system are mostly shovel-like thrust faults, which detach from the Paleozoic basement and pinch out in the Upper Jurassic salt-gypsum rock bed (Figure 2). The reverse faults are quite complex on the plane, trending NEE, NE and nearly SN. The NEE-trending faults are present in a limited area, as the product of reformation of the Permian-Triassic normal faults during the Neogene, such as the Zolamargen fault. The NE-and SN-trending faults take majority, which often intersect to form the arc-shaped thrust faults that control the development of folds. These faults were formed during the Neogene.

3.2 Structural Style

According to the thrust fault-related fold theory, the pre-salt compressional structures can be divide into two types: the fault-bend fold and breakthrough fault-propagation fault.

The fault-bend fold is the fold formed by thrust geologic body slipping along the fault surface and deforming kink-line (Jia et al., 2002) In the study area fault-bend folds are characterized by very short front wing, long back wing and the axis in close proximity to the main fault. A typical example is the Hojagurluk structure(Figure 3-A), which is controlled by a NE-trending fault, and shovel-like on profile. This fault detaching into the basement and pinching out in the post-salt strata, has controlled the development of the fault-bend fold in hanging wall. The fold high is close to the main fault. Multiple fault-bend folds are present to the south of the Hojagurluk fold, forming a thrust imbricated fan.

The primary fault propagates along the axis of the front wing of the fault-propagation fold, giving rise to the breakthrough fault-propagation fold (Shaw et al., 2008). There are various shapes of breakthrough fault-propagation folds, including symmetrical and box-shaped ones. The fold high is far from the main fault. A typical example is the Gokhmiar fold (Figure 3-B), which is controlled by a NE-trending, detaching into the basement, and pinching out in the Kimmeridgian salt-gypsum layers. This fold has symmetrical geometry, and fold high far from the main fault Gokhmiar.

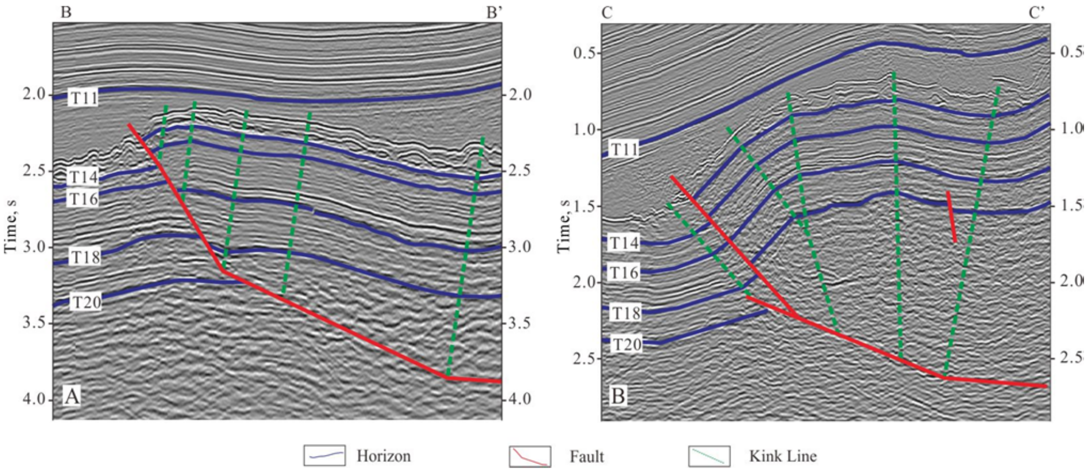

Figure 3: (A) Sesmic section of the fault-bend fold Hojagurluk. (B) Sesmic section of the breakthrough fault-propagation fold Gokhmiar. For positions see the Figure2. (T11: Top of the Kimmeridgian salt-gypsum rock, T14: Top of Callovian-Oxfordian carbonate rock; T16: Base of Callovian-Oxfordian carbonate rock, T18: Base of Middle-Lower Jurassic coal-bearing clastic rock, T20: Top of basement).

4 CONTROL OF STRUCTURAL STYLE ON RESERVOIR DEVELOPMENT

The study area was a low-energy sedimentary environment with less-developed reef-shoal facies in the Callovian-Oxfordian period (Xu et al., 2012). The carbonate reservoirs include fracture type, fracture-pore type and fracture-cave type. Structural pattern has significant influence on reservoir development.

4.1 Control of Structural Pattern on Fracture

After surveying the field outcrops A and B in the study area (Figure 2), the fracture in the Callovian-Oxfordian carbonate rock development characteristics of two typical thrust structural patterns selected were investigated.

Control of fault-bend folds on fractures: fractures are present primarily in the proximity of fold axis, near the primary fault, and include two types: fault fissures and extensional fold fissures, which form a complex fracture system by intersecting with each other. In areas far from the primary fault, fractures become less dense apparently and are distributed mainly within the kink band, and there are a few stratal detaching fissures in the fold wings. In the back wing of the fold where there is no bended deformation, regional structural fractures take the majority. There is a crushed zone in the local area of stress concentration, near the primary fault (Figure 4-A).

Control of breakthrough fault-propagation folds on fractures: fractures are present mainly in fold wings. The closer to the primary fault, the more density of fracture; a crushed zone occurs in the local area of stress concentration; the fractures are predominately fault fissures parallel to the fault strike. High-angle extensional fold fissures are present in the structural axis or bend position of strata, but much lower in density than in the proximity of the fault (Figure 4-B).

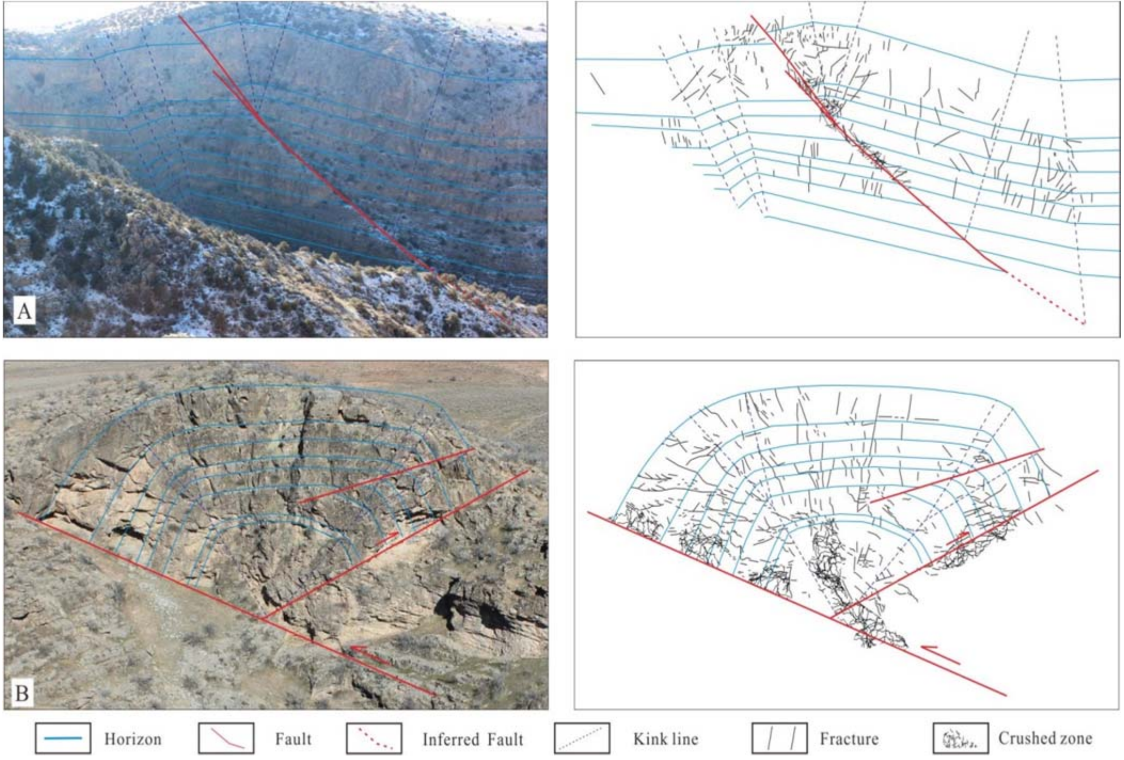

Figure 4: (A)Fracture distribution of the fault-bend folds in carbonate outcrop area. (B) Fracture distribution of the breakthrough fault-propagation fold in carbonate outcrop area. For positions see the Figure 2. The strata in the folds are the Callovian-Oxfordian carbonate rocks.The field photos are provided by Dr. Zhang Xingyang.

By comparing the above folds, it is found that they all have fractures mostly in the proximity of the primary fault. The fault-bend fold has much higher fracture density at the axis than the fault-propagation fold, but lower fracture density in the wings.

4.2 Control of Faults on Dissolution Scale

Lab analysis and microscopic observation of cores recovered from wells reveal strong dissolution in the Callovian-Oxfordian carbonate rock in the study area along fractures and pores (Figure 5). Typical dissolution actions include the deep-part hydrothermal dissolution, thermochemical sulfate reduction (TSR) and dissolution by acidic formation fluid made up of organic acid (Zheng et al., 2012;Zheng et al., 2010;Wen et al., 2010;Deng et al., 2011). The deep-part hydrothermal fluid migrated along fractures into the carbonate rock was more conducive to the formation of dissolved pores, caves and fractures. Typical examples include Well J-1 in the Zolamargen and Well A-1 in the Agary.

Well J-1 is in close proximity to the main fault in the Zolamargen fold. The reservoirs encountered are fracture-cave type, and cores recovered reveal strong dissolution along fractures. This well was tested 1.18 million cubic meters gas per day. Static and dynamic data disclose that, there are two types of dissolution fluids: ① organic matter retained in fractures suggests the dissolution fluid may be formation fluid containing organic acid; and ② high-temperature deep-part hydrothermal fluid or hot brine might be the dissolution fluid, which migrated from the deep layer into the carbonate rocks and caused strong dissolution to fractures, since the fluid inclusions contained in the samples of calcites filled in fractures have pressure-corrected homogeneous temperatures of 160 to 200°C(Figure 6-A and C), significantly higher than the formation temperature (130-150°C) of the carbonate rock in Murgab, the deepest depression within the basin (Jia et al., 2002), and the carbonate rock and the Middle-Upper Jurassic source rock in the study area.

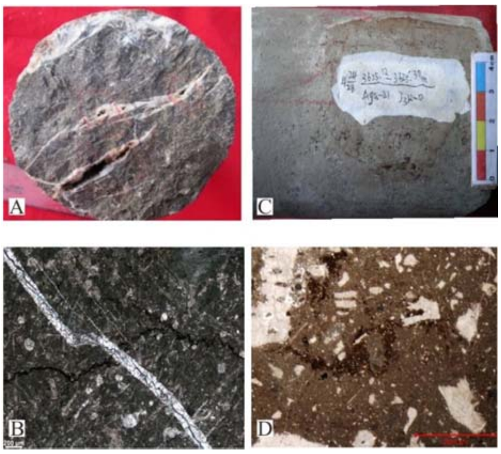

Figure 5: (A) Dissolved cave formed along fracture of well J-1, semi-filled with calcite. (B) Partially-filled fracture of J-1, impregnated by organic. (C) Grey clotted sand-size grains of well A-1, with dissolved pores. (D) Fracture full-filled with organic matter of A-1.

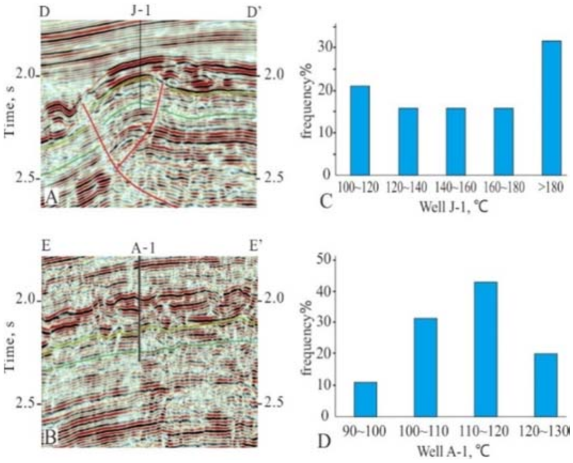

Figure 6: (A) and (B) respectively showing the seismic profiles through Well J-1 and A-1. For position see the Figure 2-A. (C) and (D) respectively showing the homogenization temperature histogram of fluid inclusions of Well J-1 and A-1. The data is provided by Dr. Ma Wenxin.

Well A-1 is located at high of the Agary. The reservoirs encountered in this well are fracture-pore type with weak dissolution, and was tested $6\times10^4m^3/d$. Static and dynamic data indicate that there are two types of dissolution fluids: ① formation fluid containing organic acid might be the dissolution fluid, as organic matter is retained in fractures; and ② acidic formation fluid resulted from TSR-generated H_2S and CO_2 dissolving in formation water might be the dissolution fluid, since the natural gas produced has a H_2S content of 0.02 to 0.04%, much higher than Well J-1 (0.0008%-0.007%). Whereas deep-part hydrothermal fluid might exert a weak dissolution to the carbonate reservoir, since the fluid inclusions contained in the samples of calcites filled in fractures have the homogeneous temperatures of 100 to 120°C, which are basically consistent with the formation temperature(Figure 6-B and D).

By comparing the locations of these wells on fold, it is revealed that the primary fault has a strong control over the dissolution to fractures: in areas adjacent to the primary fault, the deep-part hydrothermal fluid acts as the primary dissolution fluid, which has strong dissolution to fractures; and in areas far from the primary fault, the mixed organic acid and the acidic formation fluid resulted from TSR are major dissolution fluids, which have weak dissolution to fractures.

4.3 Control of Structural Pattern on Reservoir Type

It is concluded through analysis of fracture distribution and dissolution that structural style has a significant influence on distribution of fracture /fracture-pore type and fracture- cave type reservoirs.

The axis of the fault-bend fold is close to the primary fault, where fractures were well-developed and strong deep-part hydrothermal dissolution occurred, allowing for formation of fracture-cave type carbonate reservoir; and in the back wing of this type of fold, where fractures are less and the dissolution fluid dominated by acidic formation fluid enabled weak dissolution, the reservoirs are largely fracture or fracture- pore type ones.

The axis of the breakthrough fault-propagation fold is far from the primary fault, where fractures are less common and dominated by high-angle fold fissures, and acidic formation fluid acts as the primary dissolution fluid, so fracture or fracture-pore type reservoirs occur; in the front wing of this type of fold close to the primary fault, there are dense fault fissures are and strong dissolution, so fracture-cave type reservoirs developed; and in the back wing of the fold, reservoirs are largely fracture or fracture- pore type, similar to the structural high.

5 CONTROL OF STRUCTURAL STYLE ON GAS POOL TYPE

The Middle-Lower Jurassic coal-bearing clastic rock in the Amu Darya Basin reached hydrocarbon-generation threshold at the Late Cretaceous, and entered hydrocarbon generation peak at the Paleogene time, producing massive natural gas (Wang et al., 2012). The Neogene Himalayan is a critical period for trap formation, reservoir quality enhancement and hydrocarbon accumulation in the eastern part of the block. Traps begun to occur in Miocene and finalized in shape in Pleistocene. The pre-salt NE-trending thrust faults formed under the Himalayan compression acted as the pathways for hydrocarbon migration, which enabled the vertical migration of hydrocarbon along faults towards the carbonate rock and the areal migration along faults from the hydrocarbon-generating depression to the uplift zones. Structural highs adjacent to faults are favorable places for hydrocarbon accumulation, particularly the fracture- cave type reservoir zones formed as a result of tectonic disruption and dissolution, are possible sites of high-productivity fracture-cave type gas pools.

Highs of the fault-bend folds are considered favorable areas for development of fracture-cave type gas pools(Figure 7), which are highly charged with natural gas and have low water/gas ratio. Exploration wells in this type of gas pool are usually tested over a million cubic meters of gas per day. Wings of the fault-bend folds are far from the primary fault and hence may receive less hydrocarbons. Usually, these areas have fracture or fracture-pore type gas pools, which are less gas-charged, have high water/gas ratio, and low single-well gas production. Therefore, vertical wells on structural highs can achieve high production with lower drilling costs; while it is recommended to drill deviated wells in back wings with well trajectory parallel to the strike of fold as far as possible, for the purpose of encountering more regional conjugated structural fissures and enhancing the well production. For example, vertical wells were drilled in axis of various folds, such as Hojagurluk, West Zolamargen and Dashrabat. In Hojagurluk Well H-2 was tested at a million cubic meters of gas per day, with no formation water produced from the entire carbonate rock interval.

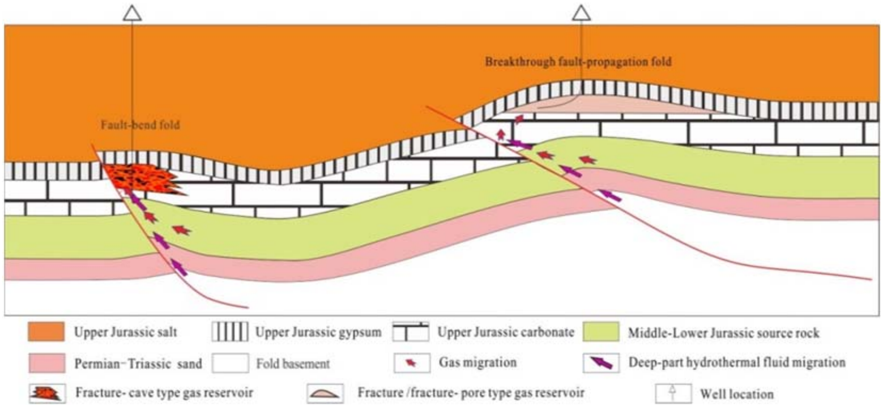

Figure 7: Patterns of gas reservoirs formation and well trajectory suggestions in different folds.

Table 1: Patterns of key folds and well-testing data (The data is provided by manager Laiyong Cao)

Name of fold	Fold type	Gas pool type	Well type	Distance to fault	Tested production ($10^4 m^3\ d^{-1}$)	Water/Gas ratio (g $10^{-4} m^3$)
Gokhmiar	Breakthrough fault-propagation fold	Fracture	Vertical	4.5km	30	18-56
Tagara	Breakthrough fault-propagation fold	Fracture	Vertical	3.5km	36	14
East Hojagurluk	Breakthrough fault-propagation fold	Fracture-pore	Deviated	2km	85	13-16
Zolamargen	Breakthrough fault-propagation fold	Fracture-pore	Vertical	4km	62	17
West Zolamargen	Fault-bend fold	Fracture-cave	Deviated	0.33km	101	9-11
Hojagurluk	Fault-bend fold	Fracture-cave	Vertical	1.1km	117	4-7

There develop fracture-cave type reservoirs in areas adjacent to the primary fault in breakthrough fault-propagation folds. However, formation of gas pools seems unlikely, since the structural position is too low to provide effective traps. In structural highs of the breakthrough fault-propagation folds that are far from the gas-source fault and went through weak Field. Its carbonate reservoir is fracture-pore type (Liu et al., 2012), the tested production is $6\times10^4 m^3$/d, and the water/gas ratio is reached $200g/10^4 m^3$. As for this type of fold, it is recommended to deploy deviated wells on high with well trajectory perpendicular to the strike of the fold, for the purpose of encountering more fold fissures and enhancing the single-well production. In the Tagara, Gokhmiar and East Hojagurluk folds, for example, deviated wells drilled on structural highs yielded much higher gas production than vertical wells. In addition, the water/gas ratio of a well is dependent fracturing and dissolution, fracture or fracture-pore type gas reservoirs were formed(Figure 7). In addition, these reservoirs have poor original physical properties, are less gas-charged and hence yield low tested gas production. The larger the distance to fault, the higher the water/gas ratio will be. Typical example include the A-1 well of the Agary Gas directly upon the distance to the primary fault; that is, the larger the distance to fault, the higher the water/gas ratio will be.

Unfortunately, drilling deviated wells based on geological understandings may not be possible for some folds, due to the national policy restriction. The tested production data of wells collected from the discovered gas fields proved the forecasted development characteristics of gas pools in different structural patterns (Table 1).

6 CONCLUSIONS

(1) There are two types of thrust structural styles in the pre-salt strata in the study area: i.e., the fault-bend fold and breakthrough fault-propagation fold. In the axis of fault-bend folds close to the primary fault, fractures are dense and several groups of fractures intersect, but in back wings of the folds there are less fractures. As for the breakthrough fault-propagation folds, there are more fractures in the front wing than the axis, and fractures in the axis are largely high-angle fold extensional fissures.

(2) Deep-part hydrothermal fluids migrated upwards along the primary fault of the fold delivered strong dissolution to fractures and pores. As a result, fracture-cave type reservoirs tend to form in axis of fault-bend folds and front wing of breakthrough fault-propagation folds, and fracture-pore type reservoirs are likely to form in back wing of fault-bend folds and pore-fracture type reservoirs in axis and back wing of breakthrough fault-propagation folds.

(3) With fracture-cave type reservoirs and close to gas source fault, structural highs of fault-bend folds are favorable positions for high-production fracture-cave type gas pools, which have high tested production of wells and low water/gas ratio. In structural highs of breakthrough fault-propagation folds that are far from the gas source fault, where weak fracturing and dissolution occurred, fracture or fracture-pore type gas pools could occur, with low tested production; and the larger the distance to the fault, the higher the water/gas ratio will be.

(4) Vertical drilling is recommended for the axis of fault-bend folds, where fracture-cave type gas pools may present. Deviated drilling is recommended for the back wing of fault-bend folds, where fracture-pore type gas pools are present. Deviated drilling perpendicular to the strike of primary fault is recommended for the axis of breakthrough fault-propagation folds, where fracture-pore type gas pools are present. Defining the development model of gas pools in different structural patterns is helpful to quickly discover the gas fields in the study area.

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