

# Main Factors Controlling Hydrocarbon Accumulation of Upper Carboniferous in M Block, Pre-Caspian Basin

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**Abstract.** The slope zone in M Block is promising zone of lithologic reservoir exploration, whereas the exploration result is low expectation due to the insufficient knowledge of reservoir forming conditions and controlling factors. In order to solve exploration problem, by using log and oil testing data, the reservoir features, accumulation conditions, hydrocarbon reservoirs genetic types and controlling factors are studied in slope zone of Upper Carboniferous KT- I . The results show there are three types of lithological reservoirs, i.e. reservoir up-dip pinching out reservoirs, lenticular lithologic reservoirs, and fault-lithologic reservoirs. The hydrocarbon reservoirs controlling factors can be summed up as follows: primary sedimentary palaeogeomorphology and later dissolution action control reservoir distribution, unconformity and interlayer fault control hydrocarbon migration and accumulation, reservoir quality controls reservoirs scale, and the barrier of tight reservoir and antithetic faults in up-dip direction control reservoirs formation. Combining reservoir prediction and its up-dip barrier conditions, two appraisal wells were conducted and yield good results.

## Introduction

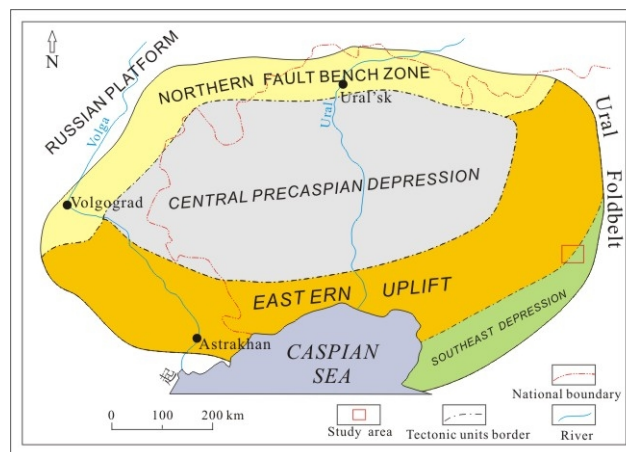
The Pre-caspian Basin in Kazakhstan is a super petroliferous basin with abundant petroleum resources (Liu et al., 2002; Qian, 2005; Liu et al., 2007; Liu and Zhu, 2007; Xu et al., 2011; Yang et al., 2014). Tectonically, the basin is subdivided into several secondary tectonic units, i.e. the northern fault bench zone, central depression, eastern uplift, and southeastern depression (Figure 1). A thick salt package, also appearing as numerous salt domes, in the Lower Permian Kungurian Stage separates hydrocarbon reservoirs vertically into suprasalt and subsalt assemblages (Figure 2). Major pay zones are subsalt Carboniferous upper carbonate KT-I and lower carbonate KT-II (Jin et al., 2007; Liu et al., 2007; Liu and Zhu, 2007), and the former has the most abundant reserves in the basin. KT-I is divided into A, Б and B from the top down. A includes A1, A2 and A3, Б includes Б1 and Б2, B includes 5 units. In block M, A1 has been denuded and only A2+A3 are preserved. A2+A3 are the major pay zones in this block.

Block M at the east margin of the Pre-caspian Basin (Figure 1) covers an area of 1900 km<sup>2</sup>. After years of efforts, the principal part of the field has been highly explored with great petroleum discoveries. The focus now is how to find more reserves. Lithologic reservoirs in the slope zone have been considered to be promising, but the exploration is below expectation, which may be due to insufficient knowledge of reservoir forming conditions, reservoir types and accumulation elements. In this paper, we use log and oil testing data of 20 wells drilled in the slope zone in the

study of KT-I related structures and reservoirs. The objective is to learn which controls hydrocarbon accumulation in the slope zone and how to conduct lithologic reservoir exploration.

### KT-I Structure Features

The Lower Permian Kungurian Stage is deposited with a thick salt package. Due to great velocity contrast between the salt package and wall rocks, the reflections below the package would be pulled upward to image "false" structures or distort real structures (Yang et al., 2012; Xu et al., 2013). Distorted structures had been erroneously interpreted as structural traps in preceding exploration, which led to drilling failures of several exploratory wells, Aa1, Aa2 and Aa3, deployed at the structural high (Miao et al., 2014). This issue has been addressed later by prestack reverse time migration and imaging, which eliminate the distortion of reflections underlying the salt package (Wang et al., 2011; Liu et al., 2012). Through depth-domain imaging and elaborate structure interpretation, subsalt structures were imaged accurately and KT-I top structure was mapped credibly (Figure 3), thus exploration efficiency could be improved greatly.



**Fig.1** Tectonic units in the Pre-caspian Basin

CHRONOSTRATIGRAPHY		LITHOLOGY	RESERVOIRS	SEALS	
PERMIAN	Lower	Kungurian	SALT		
		Artinskian	Clastic Rocks (with carbonate rocks thin beds)		
		Sakmarian			
		Asselian			
CARBONIFEROUS	Upper	Gzhelian	Upper Carbonate (KT- I)		
		Kasimovian			
		Moscovian	Upper	Mud rocks (MKT)	
		Bashkirian	Lower		
	Lower	Serpukhovian	Upper	Lower Carbonate (KT- II)	
			Lower		
		Visean	Upper		
			Middle-Lower		
	Tournaisian		Clastic Rocks		

**Fig.2** Stratigraphic column of subsalt formations in the Pre-caspian Basin

Figure 3 shows a structural map of block M in depth domain plotted with prestack reserve time

migration data. The structural high lies in the area of A10 well field in the east, and the structural low lies in the area on the west and north of B2 well field in the west. On the whole, KT-I top in block M is a slope declining towards the north and northwest. Some structural highs exist locally, but there are no complete large structural traps and small local low-relief structures. In accordance with the lowest oil-water contact in discovered reservoirs, block M is divided into an eastern uplift which is the principal oil region (with the oil-water contact at -2180 m), and a slope zone (with the oil-water contact at -2520 m). At the gently dipping monocline slope with local nosing upheavals, some reverse faults extending in NNE direction exist locally (Figure 3). This tectonic setting is favorable for the development of lithologic reservoirs.

### **Reservoir Geologic Features**

Studies show, in KT-I of block M, good reservoirs mainly occur in dolomitic flats and bioclastic beaches in restricted platforms (Miao et al., 2014). In the principal oil region in the east (which is plotted in light yellow in Figure 3, the oilfield is plotted in green), oil-bearing formations are A2+A3. Reservoir rocks are dolostone with dissolved pores and caverns. Pore space is composed of intercrystalline (dissolved) pores, intragranular dissolved pores and visceral pores (Shi et al., 2012). In the slope zone (plotted in light pink in Figure 3), oil-bearing formation is A2. Reservoir rocks are needle shaped corroded limestone. Pore space is composed of intergranular (dissolved) pores and intragranular dissolved pores (Shi et al., 2012).

As per previous studies, reservoir forming in A2+A3 in block M is related to primary sedimentary lithology and later dissolution action. The former is dominated by pre-depositional palaeogeomorphology and the latter by the karst-geomorphology in the dissolution process (Miao et al., 2014). According to palaeo-geomorphologic analysis by the residual thickness method, the slope zone during primary deposition was relatively low, and there were only some local structural highs. The principal oil region was in a high zone deposited with high-energy deposits of limestone beach, while the low-lying area was deposited with inter-beach micrite, argillaceous limestone or mudstone. High-energy deposits mostly comprised grainstone and bioclastic limestone with large primary porosity and low shale content. These lithologies in the principal oil region were apt to be corroded or dolomitized to form merged reservoir rocks with good properties. In the slope zone, only those limestone beaches at local structural highs may form small-scale reservoirs. As per palaeo-geomorphologic analysis by the impression method, the slope zone nowadays lay in the karstic highland during later corrosion, while the principal oil region lay in the karstic slope zone. The karstic highland with relatively gentle land form experienced weak corrosion because of its large surface relief. on the contrary, the karstic slope zone with large gradient experienced strong corrosion. In other words, the difference in primary lithologies results in later differential corrosion (Zheng et al., 2011). Due to the primary lithologies and weak corrosion in the slope zone nowadays, reservoir beds mostly feature small single-layer thickness and poor interconnectivity. These isolated reservoir rocks may pinch out or change into tight rocks in up-dip direction to form lithologic traps.

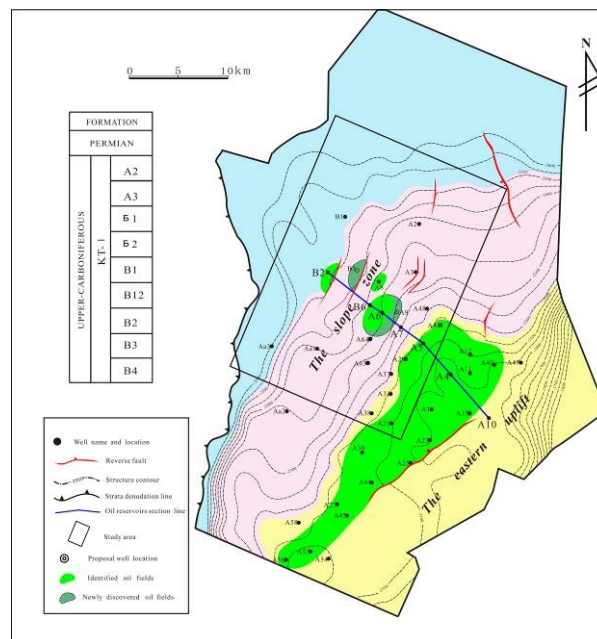
### **Hydrocarbon Accumulation Features**

**Oil Reservoirs Geologic Features.** Oil reservoirs with commercial value have been discovered in A6, A8 and B2 in the slope zone. The oil-bearing formation is A2, which is 0-50 m away from KT-I top and close to the Carboniferous unconformable surface. According to production testing data, the oil reservoir in B6-A6 well field is a unified water-oil-gas system with the gas cap in Well A6. The oil reservoir in A8 well field is a unified water-oil system. The oil reservoir in B2 well field is a

unified water-oil system. These three systems have separate oil-water contacts (Figure 3).

Due to strong heterogeneity in the slope zone, these well fields have different petrophysical properties. In Well A6 single-reservoir thickness is 21m and the porosity is 14%. In Well A8 single-reservoir thickness is 1.6-4m and the porosity is 10.5%. In Well B2 single-reservoir thickness is 0.6-1.5m and the porosity is 6.5%. Figure 4 shows a section across B2-B6-A6-A7-A5

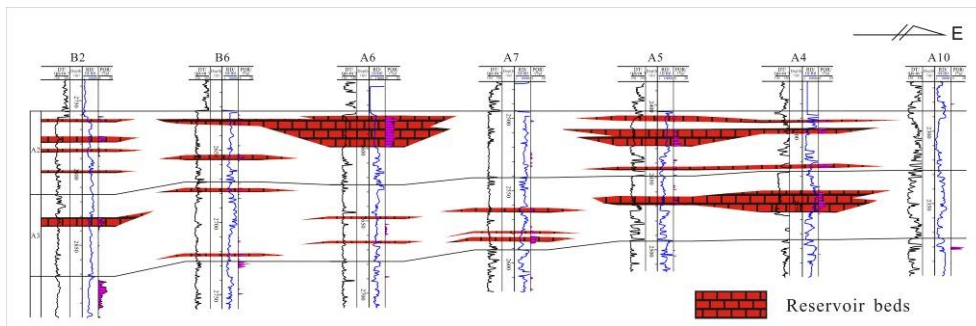
-A4-A10 for reservoir beds correlation. B2 and B6 well fields in the slope zone have thin reservoir beds with small extension. A7 well field lies in the transition zone from the eastern uplift to the slope zone, and there are no reservoir beds in A2. A5 and A4 well fields in the principal oil region have thick reservoir beds with large extension. There are no A2/A3 reservoir beds in A10 well fields. Oil reservoirs in the principal oil region are isolated by tight rocks in updip direction in A10 well fields (Miao et al., 2014). Reservoir rock heterogeneity and distribution determine oil reservoirs distribution. In B6-A6 well field oil reservoirs appear in elliptical shapes in lateral direction and in wedge shapes in vertical direction. In A8 well field oil reservoirs appear as small isolated ellipses in lateral direction and as lenticular bodies in vertical direction. In B2 well field oil reservoirs appear in fan shapes in lateral direction due to fault sealing in up-dip direction and appear in layers in vertical direction. Oil production is related with reservoir properties. Gas and oil yields in Well A6 are  $19 \times 10^3 \text{ m}^3/\text{d}$  and  $30 \text{ m}^3/\text{d}$ , respectively. Oil yield is 33 t/d in Well A8 and  $9.0 \text{ m}^3/\text{d}$  in Well B2.



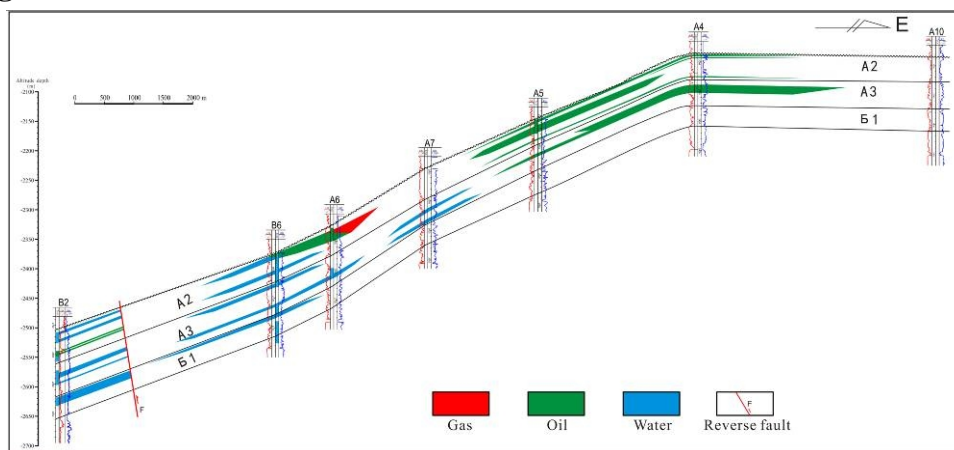
**Fig.3** KT-I top structure map in depth domain plotted with prestack reserve time migration data **Oil Reservoirs Section Analysis.** A section cross B2-B6-A6-A7-A5-A4-A10 (Figure 5) was completed for the study of oil reservoir features and distribution. In A5-A4 well field at the structural high, A2 and A3 are the pay zones with large thickness and extension. In the slope zone only A2 is the pay zone, which changes into the tight zone (for example tight rocks in A7 well field) in up-dip direction in view of the existence of the gas cap. In A6 well field reservoir thickness is large, but lateral extension is small. B2 well field at the structural low has hydrocarbon reservoirs with upper water and lower oil due to antithetic fault sealing in up-dip direction, but the volume is small, and oil and gas production is low.

**Oil Reservoirs Genetic Types.** Oil reservoirs in the slope zone may be classified into three types

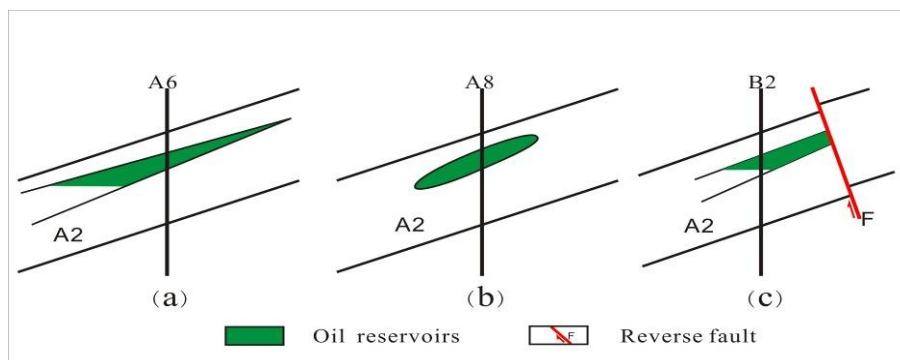
(Figure 6) as per reservoir beds correlation and oil reservoirs features. The first type is lithologic reservoirs pinching out in up-dip direction in B6-A6 well field (Figure 6a). Reservoir rocks would change into impermeable rocks in up-dip direction, which would then function as the barriers (Hu et al., 1986). The up-dip end of the oil reservoirs usually appears in wedge shape, the volume of the reservoirs is positively correlated with reservoir rock distribution, which means this kind of reservoirs is relatively large in the slope zone. The second type is lenticular lithologic reservoirs in A8 well field (Figure 6b). Lenticular or irregular reservoir rocks are enclosed by impermeable mudstone or tight rocks. Dominated by the geometry and distribution of reservoir rocks, this kind of reservoirs is relatively small in this area, but oil and gas saturation and initial production are high. The third type is faulted lithologic reservoirs in B2 well field (Figure 6c). The antithetic fault in up-dip direction usually functions as the barrier of the reservoir. In the slope zone which is a west inclined monoclinal structure, steeply dipping antithetic faults would act as the barriers. In addition, oil and gas may migrate eastward through formations or unconformable surfaces or upward along faults and then accumulate in lithologic traps sealed by faults. The third type is also important for the slope zone.



**Fig.4** A section cross B2-B6-A6-A7-A5-A4-A10 for reservoir beds correlation



**Fig.5** Oil reservoirs section across B2-B6-A6-A7-A5-A4-A10



**Fig.6** Oil reservoir types in the slope zone

## **Main Factors Controlling Lithologic Reservoirs**

**Pre-depositional Palaeogeomorphology and Later Dissolution Action Dominate Reservoir Rock Distribution.** Previous studies show A2+A3 reservoir forming in the slope zone is related to the pre-depositional palaeogeomorphology in depositional period and the palaeogeomorphology in the later dissolution process (Miao et al., 2014). During primary deposition, the slope zone nowadays lay in a low-lying area with weak hydrodynamic conditions, and some structural highs occurred locally. Therefore high-energy limestone beaches, with high shale content, were confined within a limited area. In the later dissolution process, the slope zone lay in a karstic highland with gentle land form and weak eluviation. Differential dissolution gave birth to heterogeneous reservoir rocks with small thickness and lateral extension. These reservoir rocks tended to pinch out in up-dip direction or appear in lenticular shape. Reservoir distribution is strictly dominated by the geometry and distribution of reservoir rocks.

**Unconformable Surfaces and Inter-stratal Faults Dominate Hydrocarbon Migration and Accumulation.** As per previous studies (Jin et al., 2007), the eastern subbasin (in which the study area lies) in the Pre-caspian Basin has two sets of source rocks, one in the Upper Devonian Series and the other in the Middle and Lower Carboniferous Series. TOC content is 0.1-7.8% and the kerogen is of types I, II and III, so the potential of hydrocarbon generation may be large. Several factors control hydrocarbon migration and accumulation (Jin et al., 2007). In general hydrocarbon would move towards the uplifted zones or monoclinical zones close to the source depression along unconformable surfaces in lateral direction (Gao and Zha, 2010. Gao et al., 2013) and along faults and porous permeable layers in vertical direction.

Several subsalt regional unconformable surfaces (Barde, J. P., et al., 2002; Jin et al., 2007 ; Xu et al., 2011), between the Devonian and Carboniferous, inside the Carboniferous (between the Bashkirian Stage and Moscovian Stage and between the Moscovian Stage and Kasimovian Stage), between the Upper Carboniferous and Lower Permian, and between the Lower Permian Artinskian Stage and Kungurian Stage, exist in block M. These unconformable surfaces would act as the pathways for hydrocarbon migration. In addition, reservoir rocks closing to the unconformable surfaces tend to be altered (Zhao et al., 2009). Upper Carboniferous formations in the west of block M have been extensively denuded (Figure 3), and MKT and KT-I have been denuded entirely in some areas, consequently hydrocarbon may be prone to move upward and then along unconformable surfaces into structurally higher traps as lower source rocks become closer to upper unconformable surfaces. In summary, oil-gas in block M would migrate along unconformable surfaces in lateral direction and along faults or porous (and vuggy) permeable formations in vertical direction.

**Reservoir Properties Dominate Reserves Volume.** Reservoir properties are dependent on primary lithologies and later diagenesis (corrosion). Oil-gas saturation and production are directly related to reservoir properties and volume. Reservoir rocks in the slope zone feature strong heterogeneity and small thickness, the single-layer thickness is generally 0.6-4.0 m and may reach 21 m at most, the porosity is 6.5-14%. In view of small reservoir thickness, small lateral extension and poor interconnectivity, only those reservoir rocks with faults or microfractures on the migration pathways may be effective. Oil reservoirs discovered in A6 and A8 well fields are all at A2 top close to the unconformable surface (Figure 5). But in B2 well field where faults function as migration pathways and barriers in updip direction, and lithologic reservoirs concentrate in the middle and lower parts of A2. Petroleum production differs a lot owing to the discrepancies in reservoir properties. Oil and gas yields are high in A6 well field and low in B2 well field. Therefore

the discoveries of high-yield reservoirs rely on how to find reservoir rocks with good properties and large volume.

**Tight Rocks and Antithetic Faults Dominate Hydrocarbon Accumulation.** Oil and gas would first move through the slope zone which is monocline and then accumulate in the structural high in which the principal oil region lies, which means oil and gas should be captured first in the slope zone to form hydrocarbon reservoirs. As per the studies, Well A7 was drilled at the boundary between the slope zone and structural high and there are no A2 reservoir rocks in A7 well field. A6 well field is structurally lower than A7 field, the existence of the gas cap indicates tight rocks in updip direction. Therefore there may be a NNE tight zone along structural lines, which may be the barrier of hydrocarbon migration through formations.

Faults in the slope zone would also function as the barriers of hydrocarbon migration in spite of small fault throw. For example in B2 well field with small single-reservoir thickness of 0.6-1.5 m, reservoir rocks and steeply dipping antithetic faults in updip direction of reservoir rocks constitute a complete hydrocarbon accumulation system to form faulted lithologic reservoirs.

### **Exploration Results**

As per oil reservoirs typing and the analysis of hydrocarbon accumulation controls, it is suggested to focus the efforts on the prediction of high-graded reservoir rocks (thickness and lateral extension) in the slope zone, and hydrocarbon exploration should focus on the area with tight rocks or antithetic faults in updip direction. Two drilling sites, B3 and A9, have been proposed (Figure 3). The targets are faulted lithologic reservoirs in B3 field and lithologic reservoirs (in B6-A6 well field) pinching out in updip direction in A9 field. Two wells have been successfully drilled (plotted in light green in Figure 3). Well B3 yielded high-volume commercial oil flow, which indicates the exploration of lithologic reservoirs has made progress.

### **Conclusions**

- ① Reservoir rocks in block M, characterized by small thickness, short extension and strong heterogeneity, usually form isolated lithologic traps. These traps on hydrocarbon migration pathways are apt to trap oil and gas to form lithologic reservoirs.
- ② The slope zone has three reservoir types, i.e. lithologic reservoirs pinching out in updip direction, lenticular lithologic reservoirs, and faulted lithologic reservoirs. Reservoir volume is dependent on reservoir properties (porosity and permeability) and volume (thickness and area).
- ③ Hydrocarbon accumulation in the slope zone relies on the configuration of effective reservoir rocks and tight rocks or antithetic faults in updip direction. The technical issue which should be addressed first is how to predict high-graded reservoir rock distribution and barrier conditions accurately.

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