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Hydrocarbon enrichment characteristics and difference analysis in the TZ1-TZ4 well block of the Tarim Basin

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Abstract: The reservoirs in the TZ1-TZ4 well block of the Tarim Basin are complex, and the hydrocarbon enrichment shows differences. The three Carboniferous oil layers are characterized by "oil in the upper and lower layers and gas in the middle" in profile and "oil in the west and gas in the east" in plane view. In order to discuss the complex reservoir accumulation mechanisms, based on the petroleum geology and reservoir distribution, we studied the generation history of source rocks, the fault evolution and sealing, the accumulation periods and gas washing, and reconstructed the accumulation process of the TZ1-TZ4 well block. It is concluded that the hydrocarbon enrichment differences of oil layers C_{III}, C_{II} and C_I were caused by multiple sources and multi-period hydrocarbon charging and adjustment. The C_{II} was closely related to C_{III}, but C_I was formed by reservoir adjustment during the Yanshan period and was not affected by gas washing after it was formed. During the Himalayan period, different degrees of gas washing in the east and west led to hydrocarbon enrichment differences on the plane. The Carboniferous accumulation process of two-stage charging and one-stage adjustment is summarized: oil charging during the late Hercynian period is the first accumulation period of C_{III} and C_{II}; oil reservoirs were adjusted into C_I in the Yanshan period; finally gas washing in the Himalayan period is the second accumulation period of C_{III} and C_{II}, but C_I was not affected by gas washing. This complex accumulation process leads to the hydrocarbon enrichment differences in the TZ1-TZ4 well block.

Key words: Tarim Basin, enrichment difference, multi-source and multi-period charging, accumulation process

1 Introduction

The complex reservoirs in the TZ1-TZ4 well block are representative of complicated hydrocarbon accumulation in superimposed basins. Analysis of typical reservoirs is important for further understanding the rules of hydrocarbon enrichment in superimposed basins. Many achievements have been obtained in this area (Deng et al, 2000; Liu et al, 2001; Liu, 2003; Wang et al, 2004; Liu and Su, 2005; Jiang et al, 2008a). Gou et al[1] presented that the Carboniferous reservoirs in the TZ4 well block were formed at one period, adjusted and destroyed in late periods, and the oil was mainly from the middle-upper Ordovician source rocks in the Manjiaer Depression. Wang[2] proposed an idea of "multistage accumulation and multistage adjustment", and considered that the oil was mainly related with middle-upper Ordovician source rocks but the source kitchen varied in different periods. Wang et al[3] suggested that the Cambrian and Ordovician reservoirs were the results of adjustment of paleo-reservoirs. Yang et al (2008; 2009) made a quantitative evaluation of gas washing of the Tazhong reservoirs. The TZ1-TZ4 well block shows obvious differences in hydrocarbon enrichment

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characteristics. Based on previous achievements and the latest analysis and testing data, we studied the differences of hydrocarbon enrichment, discussed the mechanism that led to the differences, and finally summarized the multiple accumulation process in the TZ1-TZ4 well block.

2 General situation of TZ1-TZ4 well block

2.1 Regional geology

The TZ1-TZ4 well block is located in the east of the main horst belt in the Tazhong Uplift (Fig. 1). Its exploration started as a prelude in Tazhong and experienced two peaks. Six oil-producing layers have been found. By the end of 2008, the proved oil reserves had been 6,382×10^4 t, and the proved gas reserves had been 348×10^8 m^3.

2.2 Petroleum geology

The source rocks, which contribute to hydrocarbon accumulation in the Tazhong area, are mainly in the Cambrian–lower Ordovician and middle-upper Ordovician. The Cambrian source rock experienced three hydrocarbon expulsion peaks, which are oil expulsion in the late Caledonian, oil expulsion in the late Hercynian, and gas expulsion in the Himalayan. The middle-upper Ordovician source rock generates hydrocarbon late, and enters the oil generation peak at present (Liang, 1999; Hou, 2000; Jiang et al, 2002; Sun et al, 2005; Ma et al, 2006; Pang et al, 2006; 2007; Wei et al, 2007; Jiang et al, 2008b).

There are many reservoirs developed in the TZ1-TZ4 well block. The Carboniferous oil layers C_I and C_{III} are clastic reservoirs, while the C_{II} is a bioclastic limestone reservoir. C_{III}

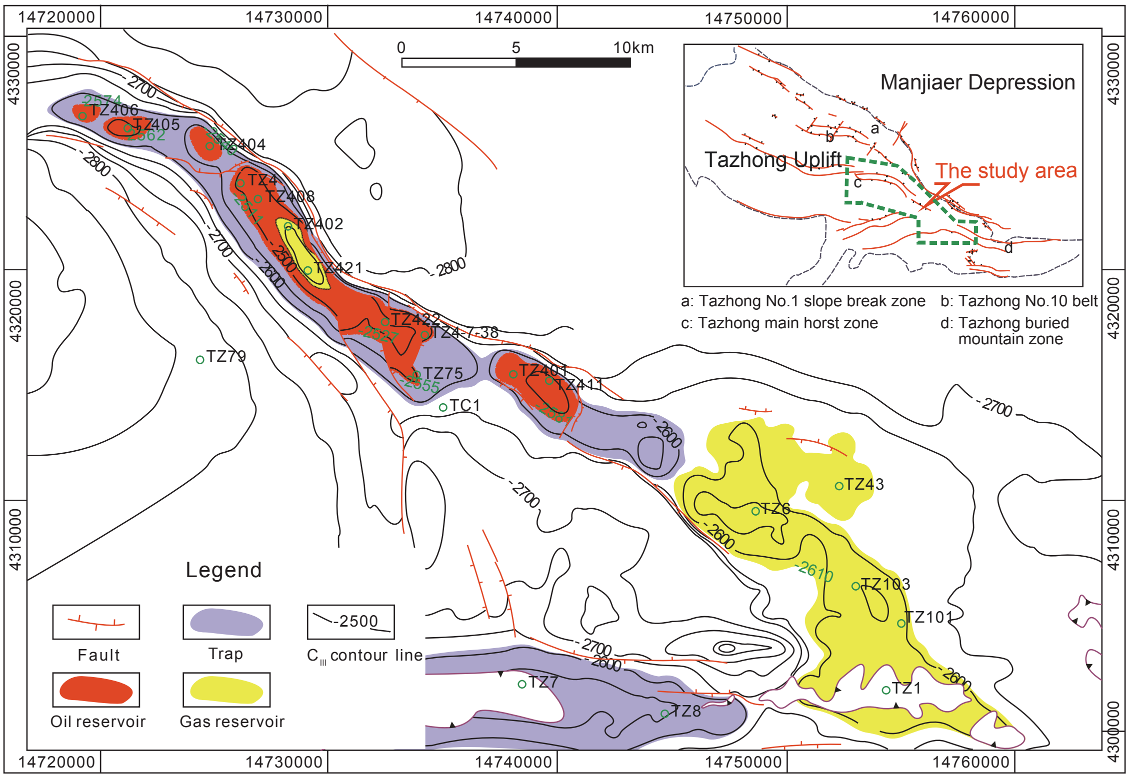


Fig. 1 Tectonic location of the TZ1-TZ4 well block

has the best reservoir quality and the Carboniferous middle mudstone segment and lower mudstone segment overlay the reservoir directly, which formed good reservoir-seal assemblages.

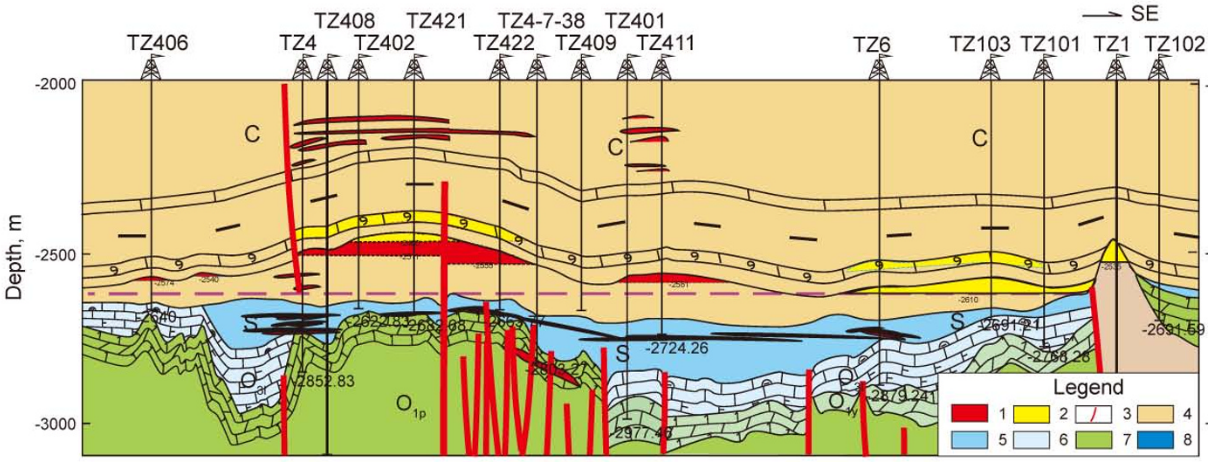
In the study area, a structural trap developed in the Carboniferous. On the whole, it is a faulted anticline controlled by faults with NW strike on both sides. The surface structural forms of C_I, C_{II} and C_{III} are basically identical, indicating their successive development (Liu, 2003; Wang et al, 2004).

The migration system in the TZ1-TZ4 well block is composed of unconformities, sandstone transport layers, faults and cracks, of which the unconformity surfaces at the top of the Ordovician and Silurian are important pathways for lateral migration. The Carboniferous Donghe sandstone serves as good transport layers for large-scale lateral migration (Pang et al, 2006). The faults in the study area are well developed and are significant pathways for vertical migration.

3 Differences of hydrocarbon enrichment in the TZ1-TZ4 well block

3.1 Different types of reservoirs

In the Carboniferous, there are three oil layers, including C_I, C_{II} and C_{III}. C_{III} is massive oil and gas reservoirs, while C_{II} and C_I are layered reservoirs. The reservoirs are controlled by anticline structures, such as the reservoirs in the TZ4 well block (Fig. 2). There are two pressure systems in the Carboniferous reservoirs, which are C_I normal pressure system (with the pressure coefficient around 1.02) and C_{II} and C_{III} overpressure system (with the pressure coefficient around 1.2) respectively.



1: Oil reservoirs; 2: Gas reservoirs; 3: Fault; 4: Carboniferous; 5: Silurian; 6: Upper Ordovician; 7: Lower Ordovician; 8: Cambrian

Fig. 2 Section of reservoirs in the TZ1-TZ4 well block

3.2 Difference of hydrocarbon enrichment

3.2.1 Oil in the west and gas in the east

In the west of the study area, the C_{III} in TZ4 well block is an oil reservoir with a condensate gas cap, and the oil has a moderate density and low viscosity. The proved oil reserves is 5,239.26×10^4 t, and the gas reserves is 178.9×10^8 m^3. The TZ6 C_{III} in the east of the study area is a condensate gas reservoir, and the oil is condensate oil with low density and viscosity. The proved gas reserves is 256.04×10^8 m^3, and the condensate oil is 656.4×10^4 t. The gas/oil ratio in the east is higher than that in the west (Fig. 3).

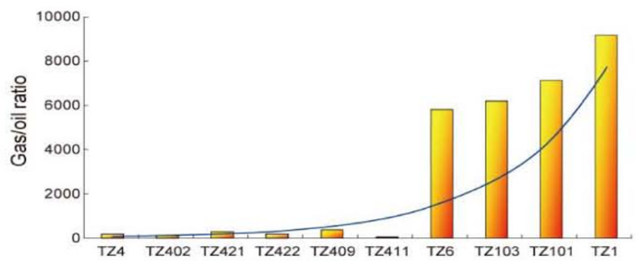


Fig. 3 Gas/oil ratios in the TZ1-TZ4 well block

3.2.2 "Oil in the upper and lower layers, gas in the middle" on the profile

In the TZ1-TZ4 well block, C_{III} and C_I are oil reservoirs, while C_{II} is a condensate gas reservoir. The characteristic of "oil in the upper and lower layers, gas in the middle" is obvious on the profile (Jiang et al, 2008a) (Fig. 2).

4 Mechanism of hydrocarbon enrichment difference in the TZ1-TZ4 well block

4.1 Hydrocarbon generation history of source rocks

We simulated the burial history, thermal history and generation history in the study area by using BasinMod software. The Cambrian–lower Ordovician source rock experienced three hydrocarbon generation periods (Guan et al, 2005; Pang et al, 2006): middle Ordovician–late Silurian, late Permian, and Paleogene–present. The middle-upper Ordovician source rock experienced two generation periods: late Permian and present.

The R_o evolution history (Fig. 4) shows that during the late Caledonian, the R_o of the middle-upper Ordovician source rock was less than 0.5% (Fig. 4, Point (1)), while the R_o of the Cambrian–lower Ordovician source rock which was generating oil then was more than 0.7% (Fig. 4, Point (2)). During the late Hercynian, the R_o of the middle-upper Ordovician source rock was 0.5%-0.7% (Fig. 4, Point (3)), and the source rock was generating oil then. The R_o of the Cambrian–lower Ordovician source rock was more than 1.0%, and the source rock was at the second oil generation peak (Fig. 4, Point (4)). In the Himalayan, the R_o of the middle-upper Ordovician source rock was still less than 1.0% (Fig. 4, Point (5)), and it is unable to generate gas, while the R_o of the Cambrian–lower Ordovician source rock was more than 1.3%, and it was generating gas (Fig. 4, Point (6)).

The multistage generation of the two sets of source rocks is the basis of the complex hydrocarbon accumulation. The geochemical characteristics and genetic types of the oils in the TZ1-TZ6 well block in the eastern part are more closely related to the Cambrian–lower Ordovician source rock (Li et al, 2008), so the oil maturity is higher than that in the western part. The higher degree of gas washing results in the difference of hydrocarbon enrichment.

4.2 Hydrocarbon accumulation periods

Fluid inclusions and authigenic illite K-Ar dating are commonly used in studying hydrocarbon accumulation periods (Jiang et al, 2000). The authigenic illite K-Ar dating data are insufficient in the Tazhong area. Combined with previous research, the accumulation period of C_{III} in the TZ4 and TZ6 well blocks is the late Hercynian, with the dating data of 246-278.4 Ma. In this period, hydrocarbon only accumulated in C_{III} and C_{II} and did not enter C_I whose K-Ar dating is 64.5-79.3 Ma, corresponding to the Yanshan

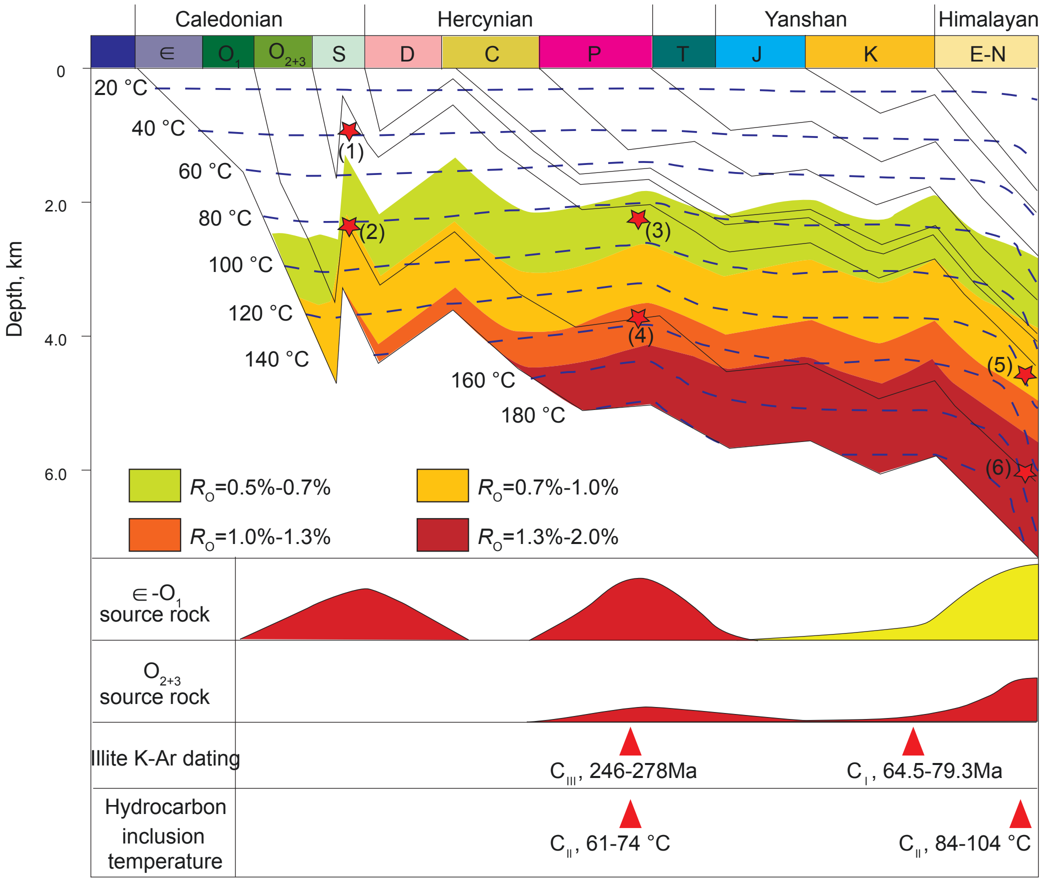


Fig. 4 Hydrocarbon accumulation characteristics in the TZ1-TZ4 well block

period (Fig. 4)[4, 5]. It is not until the Yanshan period that the hydrocarbon in C_{III} began to migrate along active faults into C_I and accumulated.

The samples were collected in the calcite veins of C_{II} in the TZ1-TZ4 well block and the sample slices were observed. A large number of inclusions in calcite veins were in belt-shaped distribution, but no inclusions were observed in authigenic growth of carbonates. This indicated that the hydrocarbon reservoir was formed at a post-diagenetic stage caused by tectonic movements after the Carboniferous closely related to faulting (Fig. 5).

Dark brown liquid hydrocarbon and grey gaseous hydrocarbon inclusions without bitumen were also observed (Fig. 5(a) and (b)), which showed obvious multistage accumulation and excellent preservation. It is concluded that there are two accumulation periods in the TZ1-TZ4 well block. The first is oil charging and the second is gas charging.

Analysis of the homogeneous temperature and burial history (Fig. 4) of the Carboniferous fluid inclusions shows that there are two groups of fluid inclusions in C_{II}. The temperature of the first group is 61-74 °C, representing the late Hercynian period when oil was accumulated and the temperature of the second group is 84-104 °C, representing the Himalayan period when gas was accumulated (Table 1).

According to the hydrocarbon generation history of source rocks, it is concluded that there are two accumulation periods in Carboniferous reservoirs: the late Hercynian period and the Himalayan period.

4.3 Faulting evolution and sealing analysis

Faults which were active during hydrocarbon migration were advantageous to vertical migration of hydrocarbon. At a regional scale, faulting in the late Caledonian and Hercynian matched with the generation peak of source rocks, and was advantageous to hydrocarbon accumulation and adjustment. Fault activities during the Yanshan and Himalayan periods became weak, but local faulting affected reservoir adjustment and gas washing.

At a reservoir scale, studying the sealing of faults is significant to understand the accumulation process. There are many methods to study the sealing of faults, and the fault plane vertical pressure method is widely used. The vertical pressure not only makes the fault plane become closed but also causes the deformation of mudstone inside the fault zone. If the vertical pressure of the fault plane is larger than the mudstone tensile strength (Li et al, 1998), the mudstone plastic deformation will occur, and the mudstone will fill the microfractures, which leads to the vertical fault sealing. The fault plane vertical pressure is calculated by the following equation:

$$P = Z(\rho_r - \rho_w)\cos\theta$$

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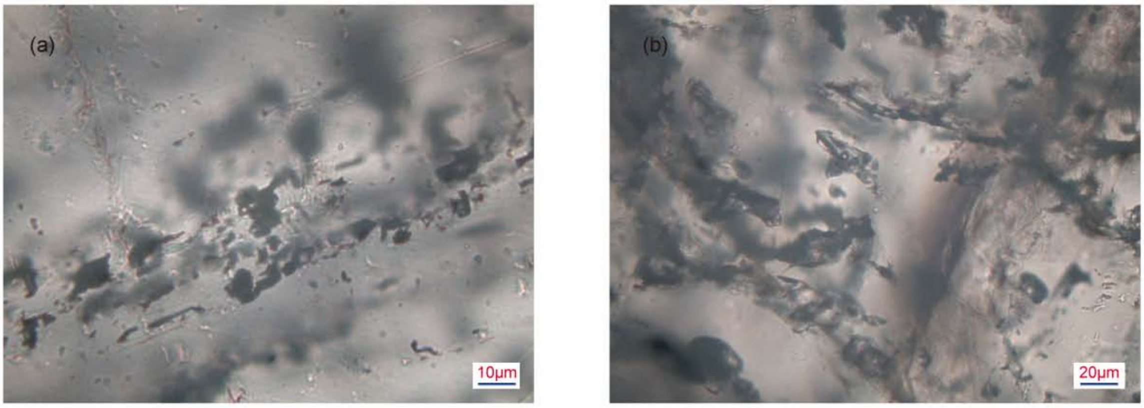


Fig. 5 Hydrocarbon inclusions in the TZ1-TZ4 well block
(a) Belt-shaped distribution, dark brown liquid hydrocarbon and grey gaseous hydrocarbon inclusions
(b) Belt-shaped distribution, grey gaseous hydrocarbon inclusion and associated grey saline inclusion

Table 1 Homogeneous temperature of the fluid inclusions in the TZ1-TZ4 well block

Well	Depth, m	Layer	Mineral	T_h, °C	Well	Depth, m	Layer	Mineral	T_h, °C
TZ4	3535.6	C_{II}	Calcite	66.00	TZ4	3553.2	C_{II}	Calcite	97-98
TZ4	3535.6	C_{II}	Calcite	68-72	TZ401	3622.2	C_{II}	Gypsum	61-63
TZ4	3542.2	C_{II}		84-89	TZ402	3526.25	C_{II}	Gypsum	71-74
TZ4	3542.2	C_{II}		90-94	TZ402	3526.25	C_{II}	Gypsum	76-78
TZ4	3553.2	C_{II}	Calcite	94-95	TZ103	3566.2	C_5	Fractured calcite	73.00
TZ103	3566.2	C_5	Fractured calcite	78.00	TZ103	3653.2	C_{II}		88.00

where, P is the fault plane vertical pressure (MPa); Z is the burial depth (m); ρ_r is the average density of overlying strata (g/cm^3); ρ_w is the density of water (g/cm^3); θ is the dip of fault plane (°). The fault plane vertical pressure of Fault F at Point A (Fig. 10) in geological history is calculated, and the sealing capacity of Fault F is evaluated according to the residual fluid pressure (Table 2).

In the late Hercynian period, the residual fluid pressure was lower than the fault plane vertical pressure, indicating that the fault was sealed, and oil was accumulated in C_{III} and C_{II}. In the Yanshan period, the residual fluid pressure was higher than the fault plane vertical pressure, indicating that the fault was unsealed, and the C_{III} oil in the TZ4 well block was adjusted upward along the active faults into C_I. In the Himalayan period, the residual fluid pressure was lower than the fault plane vertical pressure, indicating that the fault was sealed. The natural gas can not pass through Fault F, so gas can only accumulate in C_{III} and C_{II}, but can not enter into C_I. Gas washing did not affect C_I at this time.

In a word, faulting and sealing is one piece of evidence that leads to "oil in the upper and lower layers, gas in the middle" in the profile in the TZ1-TZ4 well block.

Table 2 Sealing capacity evaluation of Fault F

Period	Dip of fault plane, °	Burial depth at Point A, m	Fault plane vertical pressure, MPa	Residual pressure, MPa	Sealing capacity
Late Hercynian	65	719	5.2	4.6	Sealing
Yanshan	65	1623	11.8	11.9	Unsealing
Himalayan	65	3450	25.1	17.5	Sealing

4.4 Hydrocarbon migration and accumulation system

Hydrocarbon in the TZ1-TZ4 well block migrates vertically along the faults in general, and hydrocarbon also migrates laterally towards the structural high position inside C_{III} in the TZ4 and TZ6 well blocks. They constitute relatively independent hydrocarbon migration and accumulation systems, which cause the significant differences of hydrocarbon enrichment.

The GC-MS chromatogram of crude oil shows that the sterane and tricyclic sterane have similar characteristics vertically, indicating that the Ordovician oil sample and the overlying Carboniferous oil sample in the TZ4 well block are closely related. The Carboniferous reservoirs are results of the upward migration of hydrocarbon from the underlying Ordovician along the faults (Fig. 6).

Before the application of the Ts/Tm, Pr/nC_{17} and Ph/nC_{18} ratios, we should take account of the effect of the high maturity of oil samples on accuracy. The chromatogram shows that the maturity of oil samples from the TZ1-TZ4 well block is mainly middle to high, so that the Ts/Tm, Pr/nC_{17} and Ph/nC_{18} ratios can be used to judge the migration direction. In the migration direction, the maturity gradient decreases with increasing migration distance. The ratios of Ts/Tm, Pr/nC_{17} and Ph/nC_{18} also decrease, which confirms the truth that the Carboniferous oil and gas migrates upward from the underlying Ordovician along the faults (Fig. 7).

In the migration direction, the density and viscosity of oil samples decrease with increasing migration distance (Fig. 8). There are two migration directions in the TZ4 well block, which are from TZ4 to TZ402 and from TZ411 to TZ402. In the TZ6 well block, the migration direction is from east to west.

It is known that when the water-oil interface rose in the western TZ4 well block, it did not rise in the eastern TZ6 well block, so the two blocks belonged to different migration and accumulation systems. "Oil in the west, gas in the east" is not the result of migration fractionation.

4.5 Quantitative evaluation of gas washing

Many researchers (Thompson, 1988; Meulbroek, 1997; Meulbroek et al, 1998) discovered that *n*-alkanes of low molecular weight are fractionated from liquid into a

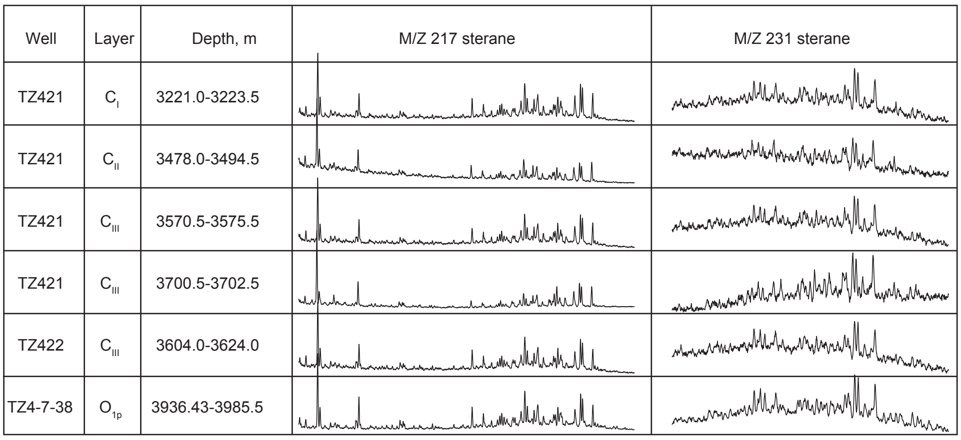


Fig. 6 Chromatogram characteristics of sterane and tricyclic sterane in oil samples from the TZ1-TZ4 well block

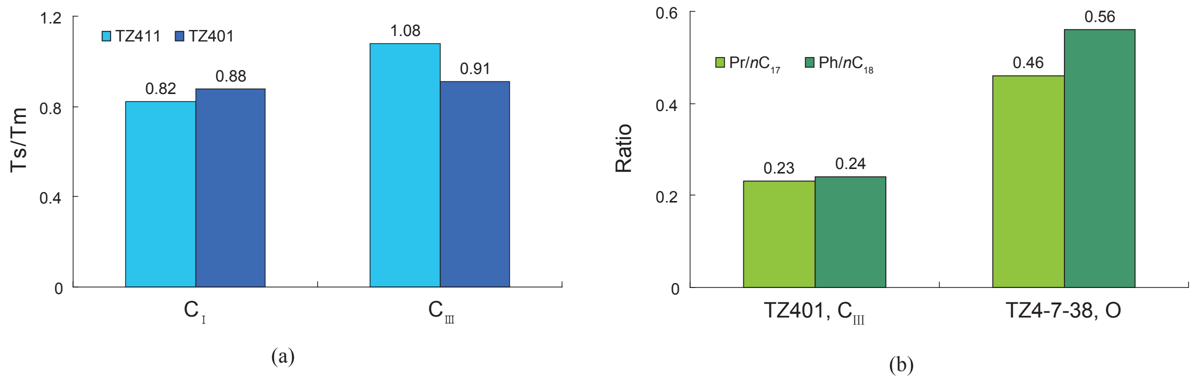


Fig. 7 Maturity characteristics of oil samples from the TZ1-TZ4 well block

coexisting vapor phase preferentially to *n*-alkanes of higher molecular weight. The *n*-alkane spectrum of gas-washing oil comprises two parts: the unfractionated part at high carbon numbers, where data are best fit by a straight line on the molar fraction plot, and the depleted part with lower carbon numbers, which deviates from the straight line fit in a regular form. The *n*-alkane carbon number at which the two parts of the spectrum connect is called the "break number" (Meulbroek, 1997; Meulbroek et al, 1998).

Therefore, the *n*-alkane spectrum of gas-washing oil can be used to determine low carbon numbers before their loss due to fractionation. Then the relationship between *n*-alkanes molar ratio and carbon numbers in practical oil samples before gas washing can be obtained (Fig.

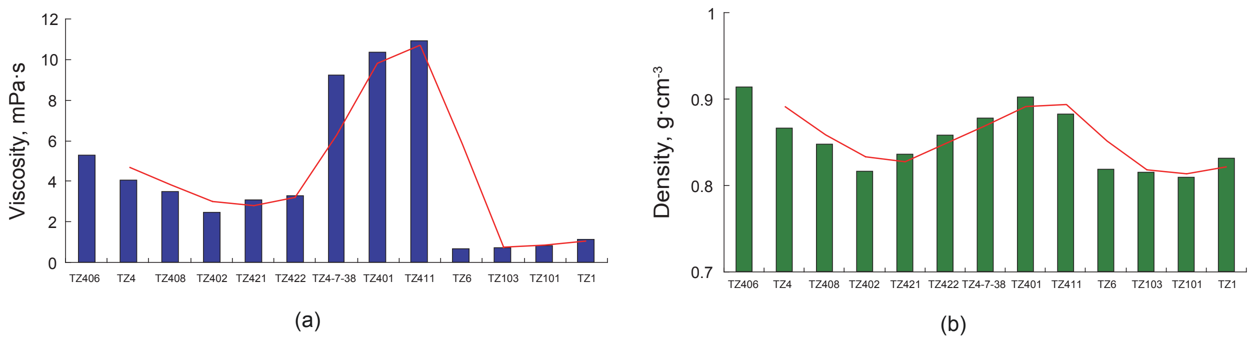


Fig. 8 Density and viscosity of oil samples in the TZ1-TZ4 well block

9(a)). Subsequently, the following equation is used to compute the loss ratio of n-alkanes Q (Losh et al, 2002).

$$Q = 1 - \left[\sum W_n(\text{practical oil samples}) / \sum W_n(\text{restored oil samples})\right]$$

where, Q is defined as the percentage of lost n-alkanes in the oil samples after gas washing and fractionation, and W_n represents the percentage of n-alkanes with n as its carbon number. The Q value represents the degree of gas washing (Losh et al, 2002).

It is also discovered that the n-alkane spectrum of TZ421 C_I is a straight line (Fig. 9(b)), which shows unfractionated oil without gas washing. Gas washing in the TZ1-TZ4 well block affects only C_{III} and C_{II}. Combined with the fault sealing research above, it is concluded that C_I did not experience gas washing because the fault was sealed in the Himalayan period, resulting in "oil in the upper and lower layers, gas in the middle" on the profile.

After analyzing the Q value, it can be found that C_{III} of the TZ4 well block experienced gas washing, but Q was less than 40% in most reservoirs (Fig. 9(c)), which indicated a low degree of gas washing in the western part. C_{III} in the TZ6 well block was condensate gas reservoir, and Q was more than 40%, which indicated a high degree of gas washing in the eastern part. Besides, the underlying Ordovician and Cambrian cores have hydrocarbon shows and asphalt which is the result of oil cracking of paleo-reservoirs in the eastern

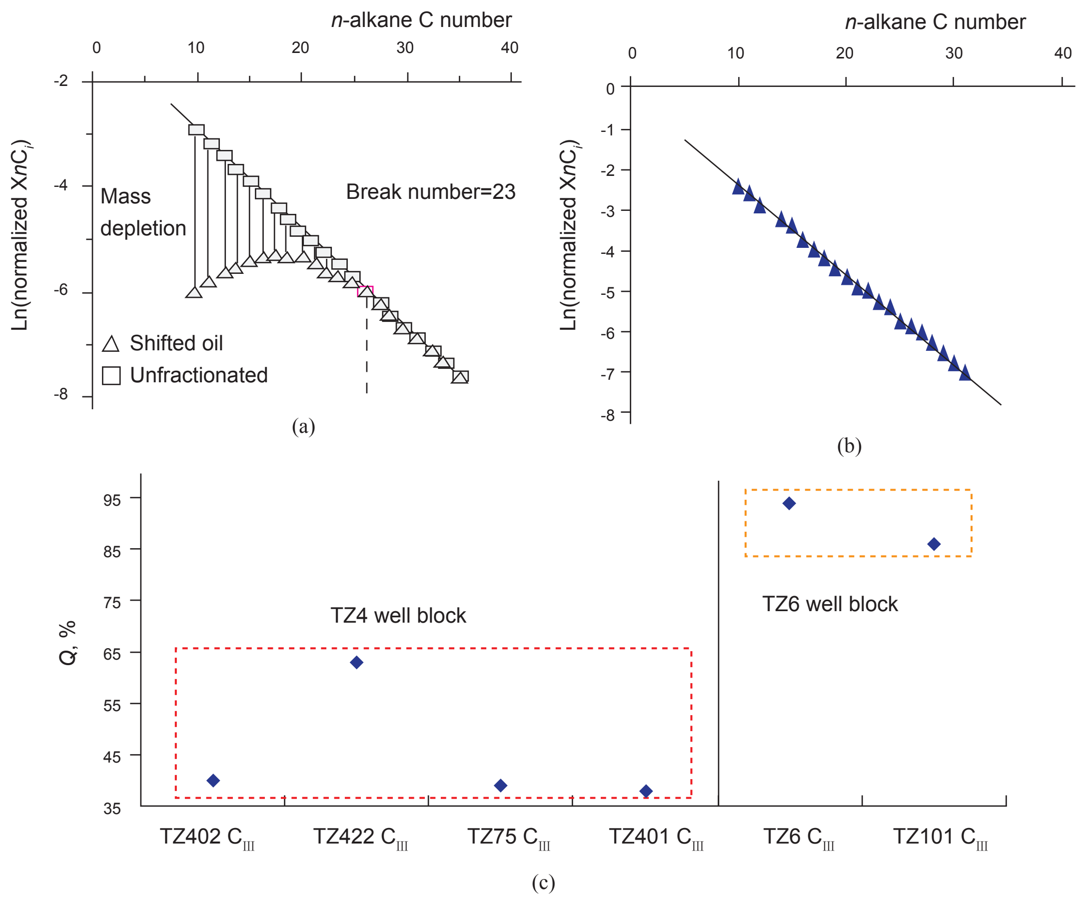


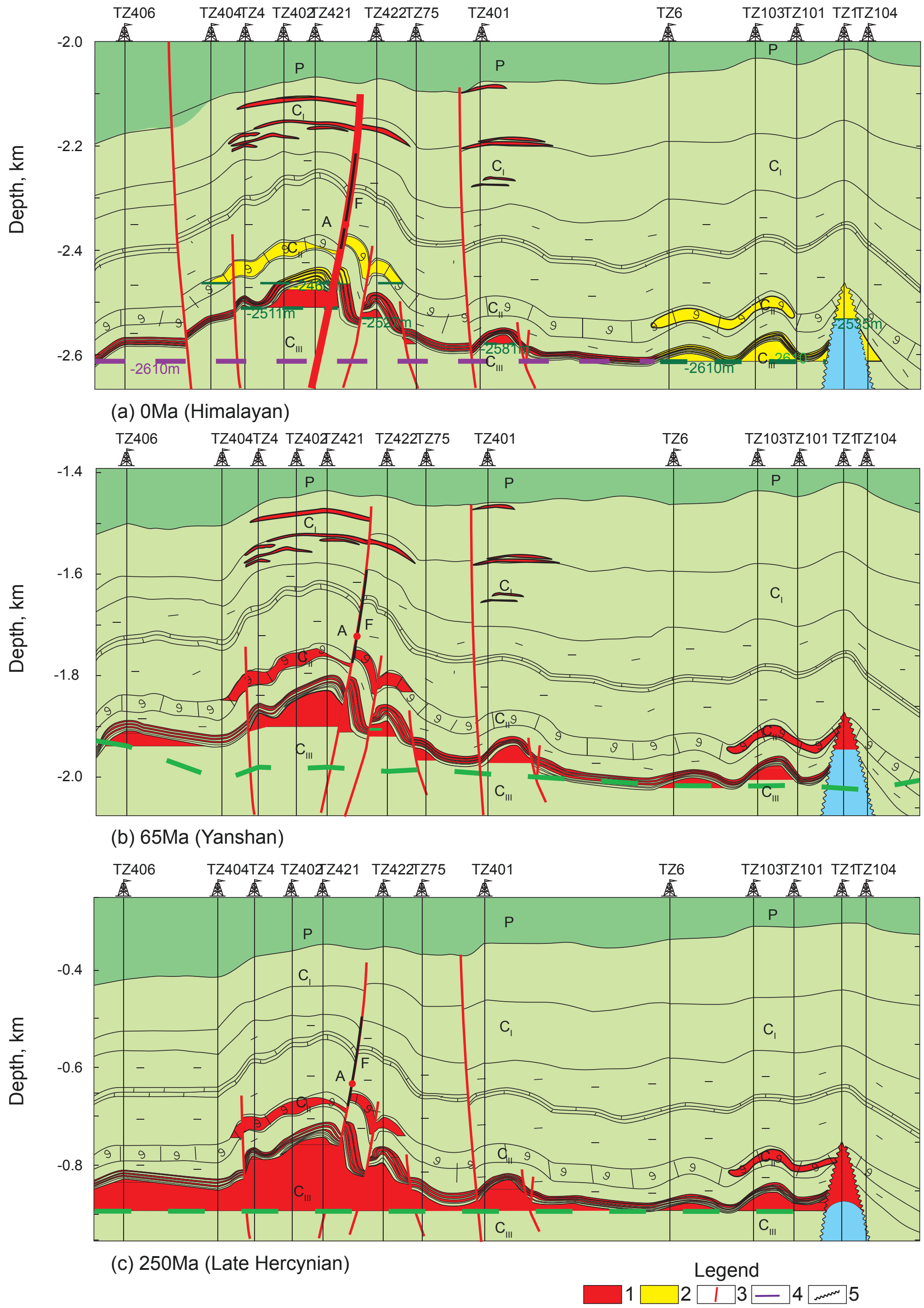
Fig. 9 Quantitative evaluation of gas washing in the TZ1-TZ4 well block
(a) Mass depletion model; (b) n-alkane spectrum of TZ421; (c) Quantitative evaluation in the study area

part, but hydrocarbon shows and asphalt are not discovered in the western part. Consequently, the eastern part where larger scale paleo-reservoirs were formed and more natural gas was generated experienced high degree gas washing. The different degree of gas washing results in "oil in the west, gas in the east" on the plane.

5 Accumulation process

Based on the analysis of hydrocarbon generation history, fault sealing, gas washing and accumulation periods, we summarized the Carboniferous accumulation process in the TZ1-TZ4 well block as two-stage charging and one-stage adjustment (Fig. 10).

In the late Hercynian period, the oil from source rocks migrated along the transport system into the Carboniferous reservoirs in the TZ4 well block. In this period the Fault F was sealed (Table 2), so oil reservoirs were formed in C_{III} and C_{II}. Meanwhile, in the TZ6 well block, oil reservoirs were formed, and C_{III} had one water-oil interface at -2,610 m in the TZ1-TZ4 well block (Fig. 10(c)).



1: Oil reservoirs; 2: Gas reservoirs; 3: Fault; 4: Water-oil interface; 5: Unconformity

Fig. 10 Hydrocarbon accumulation process in the TZ1-TZ4 well block

In the Yanshan period, Fault F was unsealed (Table 2), the C_{III} reservoir in the TZ4 well block was adjusted upward along the active faults into C_{II} and C_I, and the water-oil interface rose (Fig. 10(b)).

In the Himalayan period, the gas which was generated by the mature Cambrian–lower Ordovician source rocks and formed by paleo-reservoir oil cracking invaded the reservoirs formed in earlier stages. In the eastern part, the TZ6 well block experienced a high degree of gas washing, and condensate gas reservoirs were formed. While in the western part, the TZ4 well block experienced a low degree of gas washing, and oil reservoirs with gas caps were formed in C_{III} and condensate gas reservoirs were formed in C_{II} (Fig. 9(c)). Because the Fault F was sealed in the Himalayan period (Table 2), C_I did not experience gas washing (Fig. 9(b) and Fig. 10(a)).

6 Conclusions

1) The different degrees of gas washing result in "oil in the west, gas in the east" on the plane in the TZ1-TZ4 well block. Because larger scale paleo-reservoirs were formed and more natural gas was generated from oil cracking in the east than in the west of the study area, oil reservoirs in the east experienced a higher degree of gas washing and condensate gas reservoirs were formed. In the west, oil reservoirs experienced a lower degree of gas washing and oil reservoirs with gas caps were formed.

2) Multi-source and multi-period charging and adjustment cause "oil in the upper and lower layers, gas in the middle" on the profile in the TZ1-TZ4 well block. Multi-source and multi-period charging led to the formation of C_{III} and C_{II} reservoirs in the late Hercynian and the Himalayan periods respectively, and the oil of C_{III} and C_{II} was adjusted into C_I, which led to the formation of C_I oil reservoirs in the Yanshan period.

3) An accumulation process of two-stage charging and one-stage adjustment which results in the hydrocarbon enrichment differences is reconstructed in the TZ1-TZ4 well block: oil reservoirs in C_{III} and C_{II} were formed in the late Hercynian, then oil of C_{III} and C_{II} was adjusted into C_I in the Yanshan period and finally gas washing affected C_{III} and C_{II} but did not affect C_I in the Himalayan period.

Acknowledgements

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