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Geochemical characteristics and origin of oil from different strata in Shunbei oil and gas field, Tarim Basin

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Abstract: Volatile-light oil or oil sands have been found in the Ordovician, Silurian, and Cretaceous strata in Shunbei oil and gas field, Tarim Basin. The geochemical characteristics of oil or oil sands from these strata are obviously different. Generally, they can be divided into two genetic types: (1) Oil in the Ordovician and Silurian: The Pr/Ph value is < 1; the carbon isotope of the whole oil and *n*-alkanes is light; the $C_{21}TT/C_{23}TT$ ratio is also <1. The dibenzothiophene content is dominant among dibenzothiophene, dibenzofuran, and fluorene. These features all indicate that the oil is marine sapropelic, but their maturities are different. Oil is mature in the Silurian and highly mature in the Ordovician. (2) Oil in the Cretaceous: The Pr/Ph value is > 1.6; the carbon isotope of the whole oil is relatively heavier; the $C_{21}TT/C_{23}TT$ ratio is > 1. The oil is rich in C_{24} tetracyclic terpenoids and C_{30} rearranged hopanes. Thus, they are of continental origin. Altogether, the oil in the Ordovician and Silurian strata is from the Cambrian source rocks, which are isogenous and non-synchronous reservoirs. The oil in the Cretaceous strata mainly comes from the continental source rocks of the northern Kuqa depression.

Keywords: biomarkers; maturity; Cretaceous; Silurian; Ordovician; Shunbei oil and gas field; Tarim Basin

Shunbei oil and gas field is located in the Shuntuoguole lower uplift, Tarim Basin, with superior accumulation conditions for hydrocarbons. In recent years, the wells deployed on the NE and NW strike slip faults have obtained high-yield industrial oil and gas flow in Ordovician system. At the same time, good show of oil and gas has also been seen in the upper clastic rock series. For example, oil spots are found in well Shunbei 5-6 in the Kepingtage Formation of Silurian System. Pinhole bubbles account for about 30% on the groove face, while oil blooms account for 10%, and trace return of crude oil is observed. Weak gas indication is found in well Shunbeiping 2H and well Shunbei 5-1X in the Cretaceous system, with a correlation coefficient of 137–313, and pinpoint bubbles appear on the groove face. It is of great significance for the study of oil and gas accumulation in this area to carry out in-depth comparison of geochemical characteristics and division of the genetic types of crude oil (oil sand) in the three strata longitudinally.

1 Regional geologic aspects

Shunbei oil and gas field is mainly located in the Shuntuoguole lower uplift, extending to Shunnan area of Guchengxu uplift in the southeast, adjacent to Mangar depression and Awati depression in the east and west, and neighboring to Shaya uplift and Katake uplift in the south-north direction (Figure 1). Controlled by the Tarim Basin, especially the regional tectonic–sedimentary evolution background of Shaya uplift and Katake uplift, the Shuntuoguole lower uplift experienced multiple complex sedimentary tectonic movements. This provided favorable geological conditions for the development of source rocks, reservoirs, faults, and filling and enrichment of oil and gas [1].

Under the early-middle Caledonian tectonic compression background, many sets of slip fault zones of NE and NW strike were formed in the Shuntuoguole lower uplift. A series of strike slip fault systems with common sources finally formed in the later tectonic movements, such as inherited activity and superimposed transformation. This played an important role in controlling the longitudinal development of different strata, especially the fracture-cave type reservoir of Ordovician carbonate rocks and the enrichment of oil and gas. At present, the exploration results of Shunbei oil and gas field show that on the main fault zone, the Ordovician reservoir developed in a large scale and has high oil and gas productivity. It also proves that the strike-slip fault system has the role of controlling the storage, reservoir, and enrichment in the study area.

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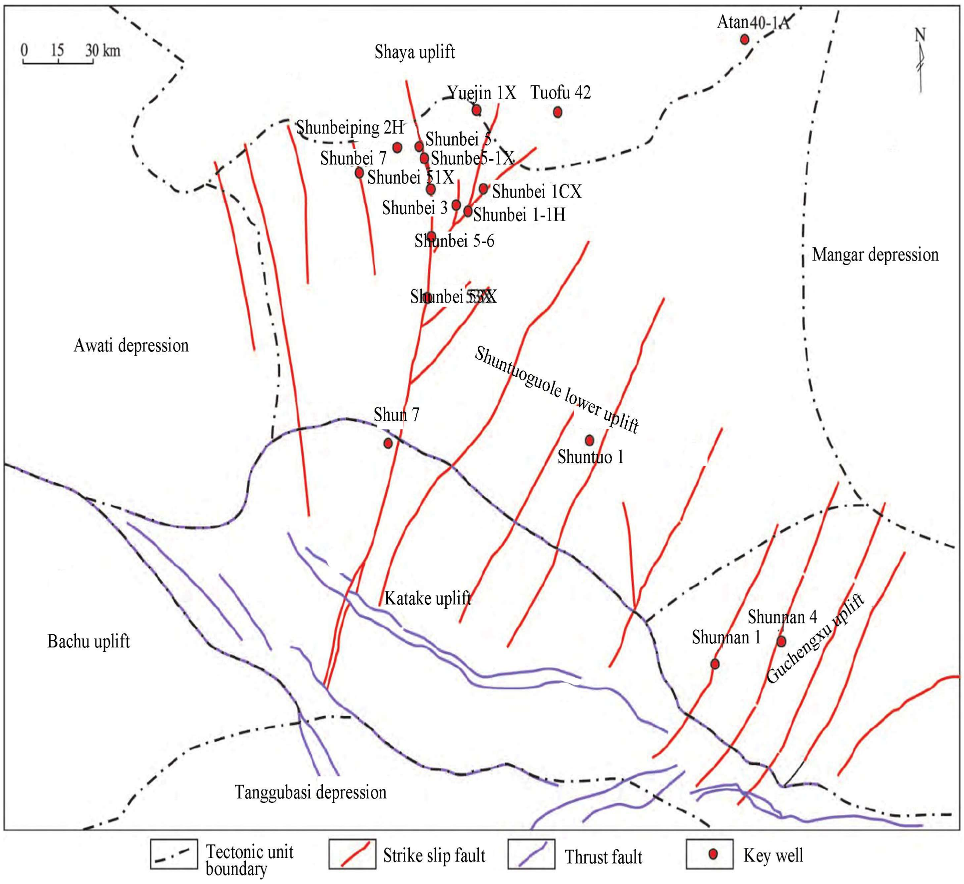

Figure 1 Location of Shunbei oil and gas field, Tarim Basin

2 Comparison of geochemical characteristics of crude oil

2.1 Chromatographic characteristics of saturated hydrocarbons

The distribution characteristics of *n*-alkanes series in crude oil (oil sand) of different strata in Shunbei oil and gas field are similar as a whole. The carbon numbers are distributed in nC_9–nC_{38}, showing a unimodal front-peak distribution. The chromatographic baseline is relatively straight. The crude oil is well preserved, and the *OEP* value is about 1.0, which is mature oil. However, the position of main peak carbon, $\Sigma nC_{21-}/\Sigma nC_{22+}$, and Pr/Ph are quite different (Table 1), which reflects the differences in source types, depositional environment, and maturity [2–4]. Among them, the main peak carbon of Ordovician oil is in the front, among nC_{11}–nC_{15}, and $\Sigma nC_{21-}/\Sigma nC_{22+}$ is 2.94–6.96, with an average of 4.73. Pr/Ph is more than 1, and the advantage of phytane is obvious. The main peak carbon of Silurian oil is nC_{18}, and the $\Sigma nC_{21-}/\Sigma nC_{22+}$ is 1.43. Compared with Ordovician oil, its maturity is slightly lower, and its Pr/Ph also shows the advantage of phytane. The main peak carbon of Cretaceous oil is nC_{17} and nC_{19}, and the $\Sigma nC_{21-}/\Sigma nC_{22+}$ is 1.81–1.85, which is between Ordovician and Silurian oils. Pristane is dominant in isoprenoid hydrocarbon, and the Pr/Ph is 1.65–1.71, which is different from the crude oil in the underlying intervals, reflecting the difference of oil and gas sources.

At the same time, with the Pr/Ph and *D* values (Ph/nC_{18}-Pr/nC_{17}) of isoprenoid hydrocarbons in oil, the depositional environments of crude oil can be well identified [5–6]. It can be seen from Figure 2 that the Pr/Ph of Ordovician and Silurian oil is less than 1.3, and the data points are well clustered. It indicates that the crude oil is coming from the same source, belonging to marine oil, while Cretaceous oil belongs to continental oil.

Table 1 Chromatographic parameters of saturated hydrocarbon of oil from different strata in Shunbei oil and gas field, Tarim Basin

Strata	Main peak carbon	Range of Carbon number	*OEP*	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	$\sum nC_{21-}/\sum nC_{22+}$
K	nC_{17}, nC_{19}	nC_{13}–nC_{37}	1.01–1.03	1.65–1.71	0.19–0.21	0.11–0.13	1.81–1.85
S	nC_{18}	nC_{14}–nC_{36}	1.01	0.68	0.32	0.43	1.43
O	nC_{11}–nC_{15}	nC_9–nC_{38}	0.97–1.09	0.73–1.02	0.30–0.35	0.35–0.51	2.94–6.96

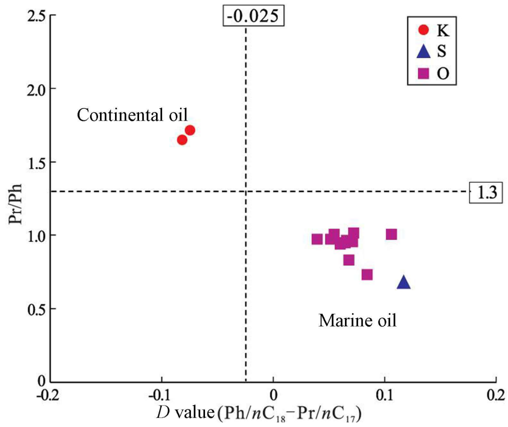

Figure 2 Depositional environment reflected by Pr/Ph and *D* of oil from different strata in Shunbei oil and gas field, Tarim Basin

2.2 Biomarker compounds

2.2.1 Terpane characteristics

The distribution of terpane compounds is closely related to the source of organic matters and depositional environments [7]. Previous studies have shown that C_{23} tricyclic terpanes are dominant in the marine source rocks and crude oil in the northern Tarim area. Its content is higher than C_{21} tricyclic terpanes, and the C_{21}TT/C_{23}TT is less than 1.0. However, the contents of tricyclic terpanes in the continental source rocks and oil are low, with C_{21} tricyclic terpanes as the main peak and C_{21}TT/C_{23}TT greater than 1.0 [8–10]. At the same time, C_{24} tetracyclic terpane is generally abundant in continental source rocks or oil, and it is also an important indicator of continental source rocks [11–12]. Therefore, the ratios of C_{21}TT/C_{23}TT of tricyclic terpane and C_{24} tetracyclic terpane/(C_{24} tetracyclic terpane + C_{26} tricyclic terpane) can be used to effectively distinguish marine and continental oil.

It can be seen from the mass chromatograms of terpenes in different strata (Figure 3) that the distribution characteristics of Ordovician and Silurian oil are similar. They are generally rich in tricyclic terpanes and hopanes, with C_{23} as the main peak of tricyclic terpane. The C_{21}TT/C_{23}TT is less than 1.0, and the C_{24} tetracyclic terpane/(C_{24} tetracyclic terpane + C_{26} tricyclic terpane), namely C_{24}TeT/(C_{24}TeT+C_{26}TT), is relatively low, distributed within 0.17–0.41, indicating that the oil is mainly from the marine sapropelic parent material. However, the Ts/(Ts + Tm), i.e. the ratio of C_{27} trisnorneohopane/(C_{27} trisnorneohopane + C_{27} trisnorhopane), is quite different. For Ordovician oil, the Ts/(Ts + Tm) is 0.49–0.78, with an average of 0.61, while that of Silurian oil is 0.38, reflecting the difference of maturity. The distribution of terpanes in Cretaceous oil sands is obviously different from those in Ordovician and Silurian oil. Since its abundance of tricyclic terpanes is obviously low, the C_{21} tricyclic terpanes are dominant, and the C_{21}TT/C_{23}TT is greater than 1.0. The C_{24}TeT/(C_{24}TeT+C_{26}TT) is as high as 0.62–0.63, and the relative abundance of C_{30} diahopane (C_{30}DiaH) is high. The results show that under the depositional environment of oxidation to sub-oxidation and the catalysis of acid medium and clay minerals, the precursor of bacterial hopanoid is prone to rearrangement, forming diahopane [13–14]. Therefore, according to comprehensive judgment, the Cretaceous oil of Shunbei oil and gas field is continental oil (Figure 4), which is consistent with the genesis that identified by isoprenoid hydrocarbon.

2.2.2 Distribution of dibenzothiophene, dibenzofuran, and fluorene

The relative compositions of fluorene (F), dibenzothiophene (SF), and dibenzofuran (OF) in the aromatic compounds of crude oil are of indicating significance for depositional environment [15–16]. In general, the contents of fluorene in continental freshwater source rock and oil are high; those of dibenzofuran in paludal facies coal and coal-derived oil are high; those of dibenzothiophene in salt lake facies and source rock and oil in marine strongly-reduced environment are high. The compositions of fluorene (F), dibenzothiophene (SF), and dibenzofuran (OF) in the Ordovician and Silurian oils of Shunbei are similar (Figure 5), which shows that the content of dibenzothiophene is high (> 60%) and that of dibenzofuran is very low (< 2%). It indicates that the parent materials of oil are mainly in a high salinity or strongly-reducted environment, which is related to the source rock of marine strongly-reducted environment. However, in the Cretaceous oil sands, the content of dibenzothiophene decreases and those of dibenzofuran and fluorene increase, which may be from the continental freshwater source rocks in the oxidation environment.

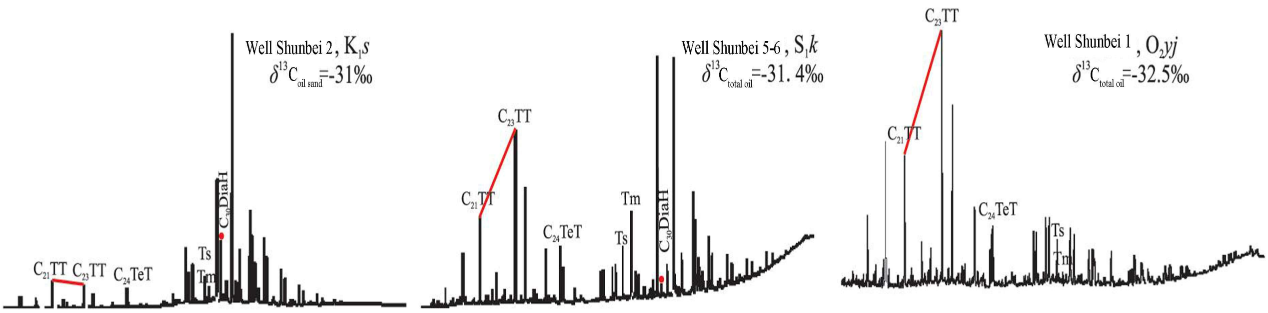

Figure 3 Terpene distributions of oil or oil sands from different strata in Shunbei oil and gas field, Tarim Basin

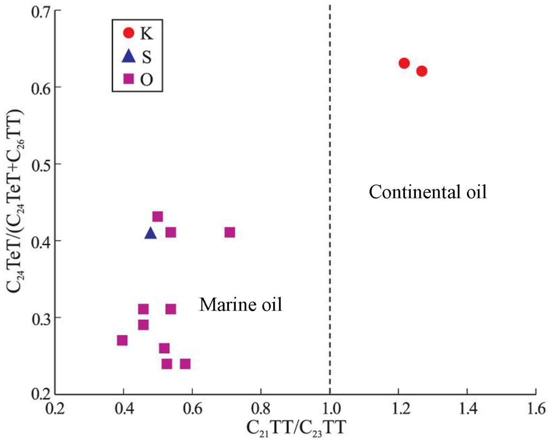

Figure 4 Correlation between $C_{21}TT/C_{23}TT$ and $C_{24}TeT/(C_{24}TeT + C_{26}TT)$ of oil from different strata in Shunbei oil and gas field, Tarim Basin

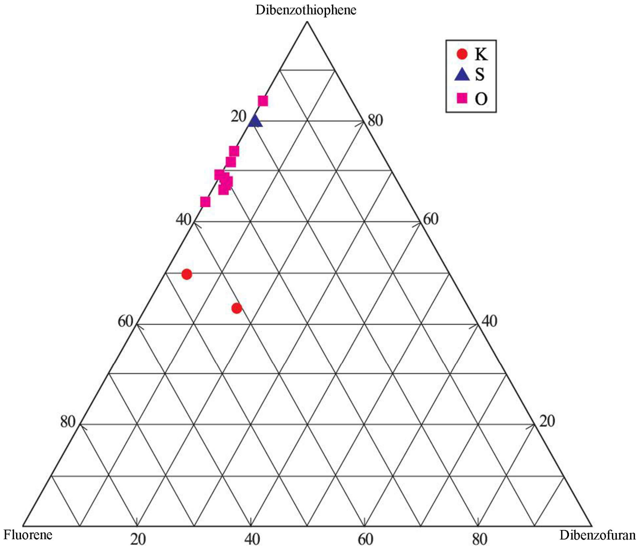

Figure 5 Triangular plot of dibenzothiophene, dibenzofuran, and fluorene in oil from different strata in Shunbei oil and gas field, Tarim Basin

2.3 Characteristics of carbon isotopic composition

The carbon isotopic composition of oil mainly inherits that of its parent organic matters. The total-oil carbon isotope values of Ordovician and Silurian oils in Shunbei area are distributed from −31.4‰ to −32.5‰, with an average of −31.99‰, showing the characteristics of marine oil (Figure 6). The carbon isotope of Cretaceous oil sands is relatively heavy, ranging from −29.9‰ to −31.1‰, which is close to that of Cretaceous oil sands from Triassic source rocks in Halahatang–Yingmaili area [17].

The compound-specific carbon isotope of hydrocarbons can reflect the source of a single compound from the molecular level, which has more obvious advantages than the carbon isotopes of the total oil and their group components. Previous studies on compound-specific carbon isotopes of saturated hydrocarbons in oil have been widely carried out. It is generally believed that the carbon isotope values of *n*-alkane monomers in the oil with different genetic types are mainly determined by the depositional environment of the parent sources and the related source input [18–19]. In Shunbei area, the carbon isotope distributions of the saturated hydrocarbon in Ordovician and Silurian oils are basically the same. The curves are stable, and the carbon isotope value is relatively small, which is less than −33.0‰, reflecting that they have the same source. The compound-specific carbon isotope of the Cretaceous oil is obviously heavier, and the curve is serration–downward inclined distribution (Figure 7). It indicates that its parent source is significantly different from that of the underlying formation.

3 Genesis analysis

According to the analysis of the actual drilling and field outcrop data, the Pr/Ph of the source rocks in the Cambrian Yu’ertusi Formation of Tarim Basin is mostly less than 1. The tricyclic terpane and hopaneshopanes are rich, and the $C_{21}TT/C_{23}TT$ is less than 1.0. The C_{24} tetracyclic terpane is low (Figure 8), and the carbon isotope of kerogen is light (about −32‰ to −35‰). The Ordovician and Silurian oils of Shunbei oil and gas field are similar to the source rock of Yu’ertusi Formation in geochemical characteristics, so it is considered that it comes from the source rock of the Cambrian Yu’ertusi Formation [1].

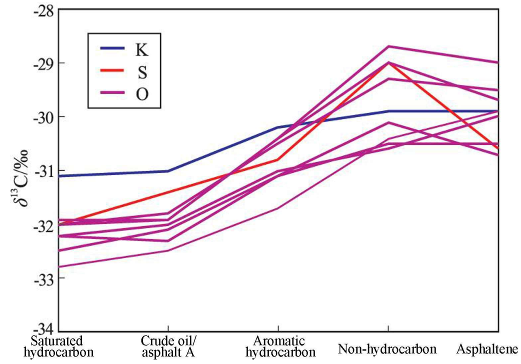

Figure 6 Carbon isotopic distribution of oil or oil sands and their groups from different strata in Shunbei oil and gas field, Tarim Basin

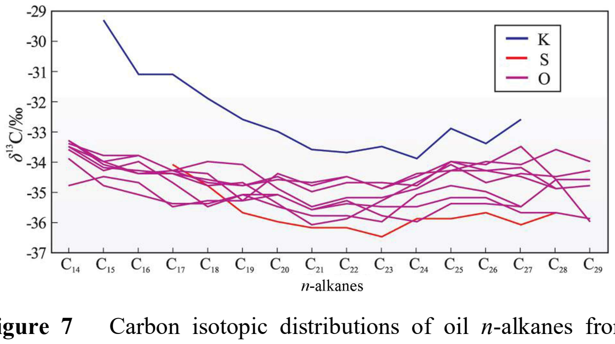

Figure 7 Carbon isotopic distributions of oil *n*-alkanes from different strata in Shunbei oil and gas field, Tarim Basin

Previous studies have confirmed that the continental oil of Kuqa depression in the north can migrate to the Cretaceous system in the Rewapu area of Halahatang for a long distance, so the oil in Shunbei oil and gas field in the south of Kuqa depression may also be continental. The biomarker characteristics of Triassic lacustrine mudstones in Kuqa depression are as follows: the Pr/Ph is high, ranging from 1.5 to 3.56; the tricyclic terpane is low in abundance; the C_{21} tricyclic terpane is the main peak; the C_{24} tetracyclic terpane is high in relative content [17,20]. This is consistent with the characteristics of Cretaceous oil sands in Shunbei oil and gas field. The analysis shows that the Cretaceous oil in Shunbei area comes from the northern Triassic source rocks.

To sum up, the Ordovician and Silurian of Shunbei oil and gas field are marine reservoirs of the same source but different periods, and the maturity of Silurian oil is low; while the Cretaceous oil is continental oil, which is closely related to the regional structural settings, source rocks, fault evolution, etc. From the late Caledonian Period to the early Hercynian Period, the source rocks entered the generation and expulsion period of hydrocarbons, and a large amount of oil was filled into the reservoirs. In the fault zone with strong activities and upward extending to Silurian system, the oil and gas were fully filled, forming reservoirs in the Ordovician and Silurian systems. It was destroyed and dispersed in the early Hercynian structural uplift and erosion, forming the asphalt widely distributed in Ordovician and Silurian systems in Shunbei area at present. In the late Hercynian period, the source rock continued to generate and expulse hydrocarbons. The inherited activities of faults connected the oil sources at the bottom, and hydrocarbons migrated upward to form light oil reservoirs in Ordovician and Silurian systems (Figure 9). In Himalayan Period, the source rock was in the stage of generating condensate oil and gas [1], but the overall movement of the fault was weak in this period. At the same time, the thickness of regional mudstone caprock of overlying upper Ordovician series was large, and the top sealing property was good. It was difficult for oil and gas to break through the mudstone of overlying thick layers and enter the Silurian system, so oil and gas accumulated in the lower Ordovician system along the fault, resulting in the higher oil maturity of Ordovician system than that of Silurian system. During the Yanshan–Himalayan Period, regional structural inversion took place in the northern Tarim area, and the Cretaceous system showed a monoclinal structural pattern of low in the north and high in the south as a whole. This provided a favorable basis for the migration of continental oil and gas from north to south in Kuqa depression (Figure 9). In the early stage, a large amount of oil and gas from the Triassic lacustrine source rocks of Kuqa depression in the north were discovered in the Cretaceous of Halahatang and southern Yingmaili [17]. It proved that the continental oil and gas in the north could migrate laterally to Shunbei oil and gas field through faults, unconformities, and sand bodies in a long distance.

4 Conclusions

(1) The Ordovician and Silurian oils in Shunbei oil and gas field have similar geochemical characteristics, and they are both marine oil from the source rocks of the Cambrian Yu'ertusi Formation, but their maturities are different: The oil in Ordovician system is highly mature, while that in Silurian system is mature. According to the analysis of regional geological settings, the two reservoirs are of the same source but different accumulation periods.

(2) The characteristics of Cretaceous oil in Shunbei oil and gas field are obviously different from those of Ordovician and Silurian oils. It is the continental oil with large carbon isotope value, which may be lacustrine oil generated from the Triassic source rocks in the northern Kuqa depression.

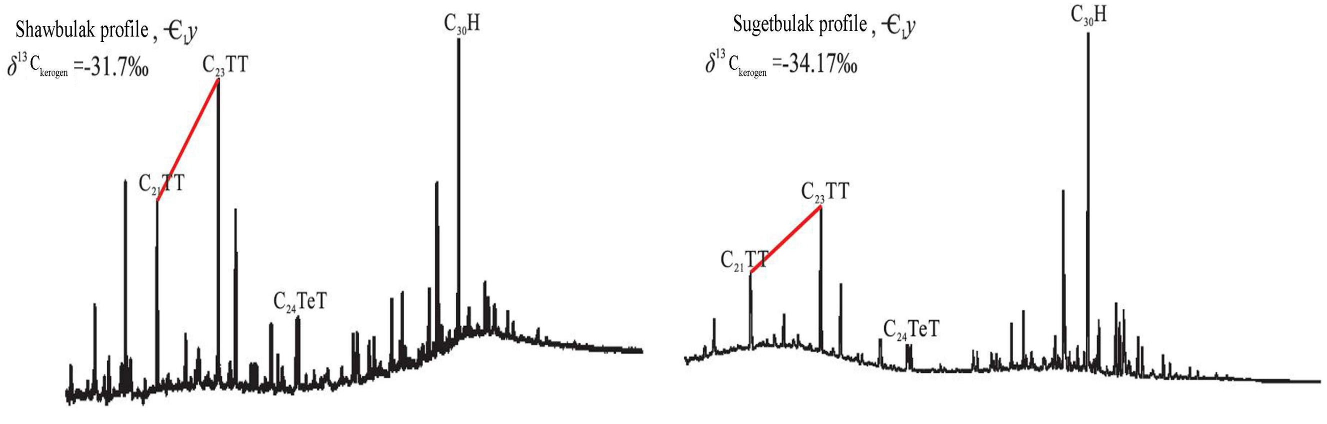

Figure 8 Terpene distribution of Cambrian source rocks in Yu'ertusi Formation, Tarim Basin

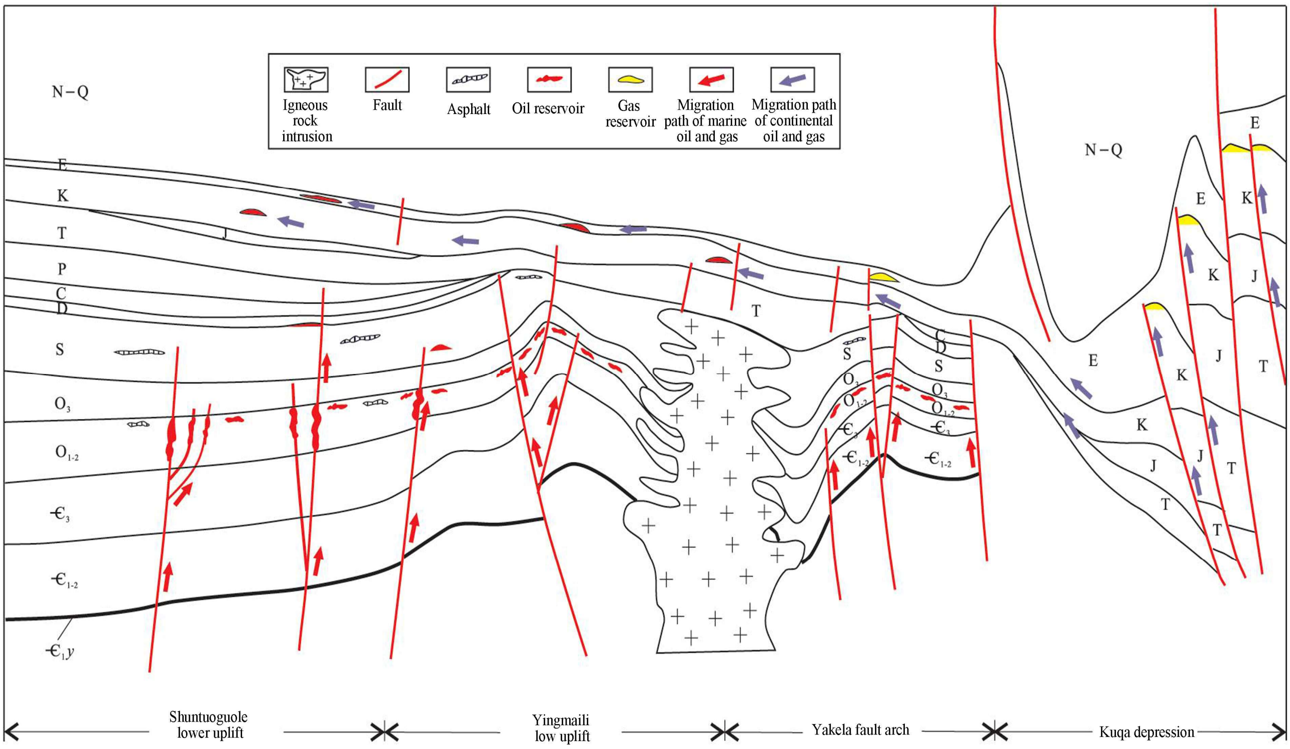

Figure 9 Model of hydrocarbon migration and accumulation in Shunbei oil and gas field, Tarim Basin

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