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Marine and Petroleum Geology 17 (2000) 1–12

Marine and Petroleum Geology

The Tazhong hybrid petroleum system, Tarim Basin, China

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Received 23 April 1999; received in revised form 11 August 1999; accepted 16 August 1999

Abstract

The Tazhong petroleum system is geographically located in the central Tarim Basin, including the Tazhong Uplift, the North Slope and the southern area of the Manjiaer Depression. The total thickness of early Palaeozoic to Cenozoic sediments reaches 6500–9500 m. The Manjiaer Depression and the North Slope are the two major petroleum source areas with three sets of source rocks: Cambrian black shales and Ordovician dark carbonates of the Manjiaer Depression and Ordovician argillaceous limestones of the North Slope. There are three sets of reservoir-cap rock combinations in this petroleum system. The main periods for oil generation from these source rocks occurred during the middle Silurian to Early Devonian, late Carboniferous to Early Triassic, and Tertiary. There were three corresponding phases of petroleum migration. Well developed thrust faults and unconformity surfaces in this area provided the main pathways for petroleum migration. As some of the faults cut through all the lower Palaeozoic strata, the oil in any given reservoir rock may be actually a mixture of oils from different sources, complicating the origin and properties of the hydrocarbons in the reservoir, and forming a hybrid petroleum system. The formation of a typical oil and gas pool in this petroleum system may be attributed to one or all of three petroleum events which were closely associated with the regional tectonics. The first event occurred in the early Palaeozoic tectonic cycle and the generated oil accumulated in lower Silurian sandstone. The second event occurred in the late Palaeozoic tectonic cycle and formed light oil pools mainly in lower Silurian and Ordovician reservoirs. The third event took place during the Cenozoic tectonic cycle and formed normal crude oils. The oil and gas generated from different sources in different phases may co-exist with one another in a reservoir rock. However, the commercial oil and gas pools are related to the Cenozoic and late Palaeozoic events.

Keywords: Hybrid petroleum system; Petroleum event; Tazhong Uplift; North Slope; Tarim Basin

1. Introduction

The Tazhong Uplift is the most important area of petroleum accumulation in the Tarim basin and it has had about fifteen years of exploration history (Kang, Jio, Jiang & Huang, 1989; Wang & Zhang, 1992). In recent years, much work has been done on the petroleum geology and geochemistry of this area (Hao, Gao & Wang, 1996; Kang, 1992; Wang, 1986; Zhang, 1990; Zhou & Jiang, 1984), and substantial information has been obtained on the origin of the oil and gas. The Tazhong Uplift and its North Slope (both areas together are referred to as the Tazhong area by Chinese geologists), together with the southern area of the Manjiaer Depression, constitute a complete petroleum system including sources, migration pathways, reservoirs, cap rocks and traps (Huang, 1994; Xiao & Liu, 1998; Xiao, Liu & Fu, 1996). More than 20 oil and gas pools and structures have been discovered so far (Hao et al., 1996; Huang, 1994; Kang, 1992; Xiao and Liu, 1998). However, this petroleum system is complex. Previous studies have indicated that there are several sets of source–reservoir–seal combinations existing in this area, and oil and gas generated from different source rocks during different geological periods might migrate into the same reservoirs in the Tazhong area where mixing could occur. The properties and origin of oil and gas in such reservoir rocks

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0264-8172/00/$ - see front matter
PII: S0264-8172(99)00050-1

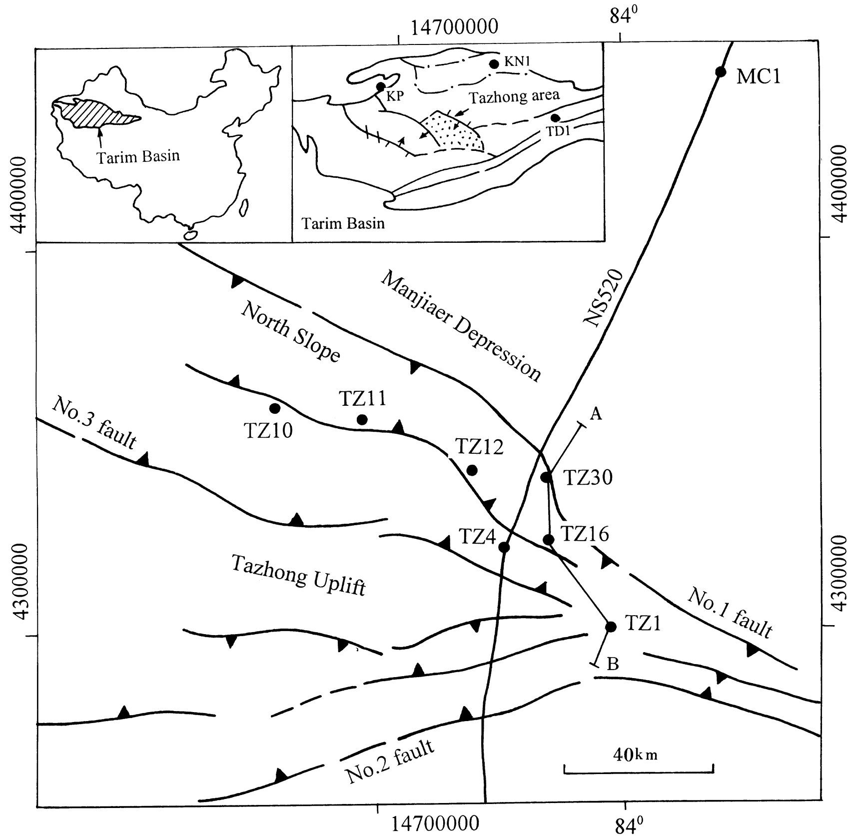

Fig. 1. Tectonic framework and location of the study area.

are complicated and difficult to explain using the conventional theories applied to petroleum systems (Li, 1998; Liang, 1999; Lu, 1997; Mu, Xiao & Yong, 1997; Xiao & Liu, 1998; Xiao et al., 1996; Zhuo, Tan & Qiou, 1997). The primary aim of this paper is to evaluate geological and geochemical information related to the formation of oil and gas pools in the Tazhong area and to develop the concept of a hybrid petroleum system for the Tarim Basin.

2. Geological background

As described above, the Tazhong petroleum system includes the Tazhong area and the southern part of the Manjiaer Depression. The focus of the present study was the Tazhong area because more than 30 deep boreholes have been drilled there recently and some have penetrated lower Palaeozoic strata. However, no borehole has penetrated lower Palaeozoic strata in the Manjiaer Depression. The Tazhong area is about 230 km from east to west and 120 km in a north–south direction, covering an area of about 2.8×10^4 km^2 (Fig. 1). The Manjiaer Depression covers a huge area, about 13×10^4 km^2 (Jia, 1999), but only its southern part adjacent to the Tazhong area belongs to the Tazhong petroleum system. There are no data on the exact size of this part but it has been estimated to be about 3.5–4.0 $\times 10^4$ km^2 (Xiao & Liu, 1998).

The Tazhong area contains sediments of all ages from Cambrian to Tertiary with a total thickness of 6500–9500 m that overlie Archaean and Proterozoic crystalline basement (Yung & Liu, 1992; Zhang, 1992). The sedimentary facies underwent evolution from an early Palaeozoic marine carbonate platform, through late Palaeozoic alternating marine and continental deposits, to Mesozoic and Cenozoic continental fluvial deposits, with thicknesses of 3500–5000 m, 1500–2000 m and 1500–2500 m, respectively (Fig. 2).

The present-day structures in the Tazhong area are quite unusual. The early Palaeozoic strata form a wide anticline and the later Palaeozoic occurs as a nose-shape structure which dips towards the west whereas Mesozoic and Cenozoic strata dip very gently. Therefore, the Tazhong area is in fact a palaeo-uplift (Fig. 3). A few large thrust faults in the east-west direction have developed dividing the Tazhong area

Period	Thickness (m)	Lithologic succession	Lithology description	Depositional Facies
Q	200 – 300		Sand, conglomerate	Continental Disposits
R	500 – 2000		Upper part: grey to yellow siltstone and mudstone; lower part: brown-red sandstone and mudstone	
E	200 – 2000		Brown, grey, yellow siltstone and mudstone	
J	200 – 500		Interbedded yellow sandstone and mudstone	
T	100 – 1000		Dark grey mudstone and siltstone	
P	450 – 1500		Brown, yellow and red sandstone and mudstone	Marine-continental alternating disposits
C	400 – 700		Interbedded grey sandstone and mudstone	
D	0 – 400		Yellow sandstone	Marine disposits
S	0 – 600		Yellow sandstone and shale	
O_{2+3}	0 – 3500		Dark limestone and argillacous limestone	
O_1	2000 – 2500		Grey to dark grey dolomite and limestone, partly black shale	
Є	800 – 1000		Grey and dark grey carbonate, partly black shale	

Fig. 2. Composite stratigraphic summary of the Tazhong area (based on well and seismic data).

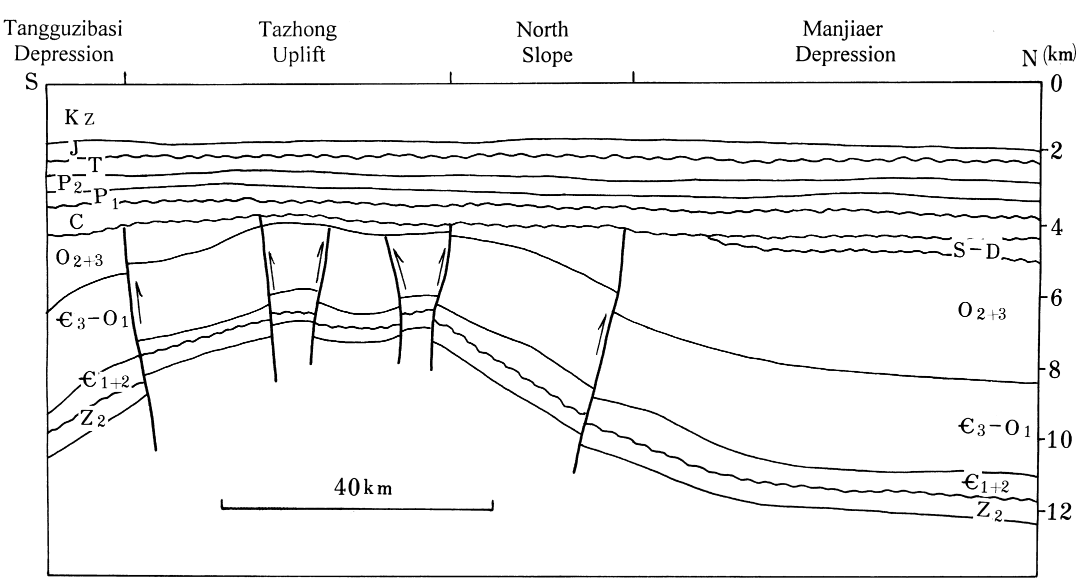

Fig. 3. NS520 interpreted seismic section.

Table 1
Geochemical data for some typical source rocks from the Tazhong petroleum system

Well	Age	Lithology	Depth (m)	TOC (%)	HI (mg/g)	EVRo[a] (%)	Kerogen type[b]
TZ10	O_{2-3}	Dark grey mudstone	4928	1.05	41	1.20	II
TZ10	O_{2-3}	Dark grey mudstone	5117	0.48	48	N/f	II
TZ10	O_{2-3}	Dark grey argillaceous limestone	5243	0.49	74	1.25	II
TZ12	O_{2-3}	Dark grey argillaceous limestone	4806	0.68	162	1.00	II
TZ12	O_{2-3}	Black limestone	5075	1.18	68	1.08	II
TZ12	O_1	Dark limestone	5298	0.47	65	1.18	II
TZ1	O_1	Dark shale	4552	0.74	32	1.65	II
TZ1	Cambrian	Dark limestone	6320	0.52	10	N/f	I
TZ1	Cambrian	Dark limestone	6500	0.54	8	2.40	I
KN1	Cambrian	Dark limestone	4865	0.78	11	2.01	I
KN1	Cambrian	Black shale	5190	0.98	10	N/F	I
KN1	Cambrian	Black shale	5350	5.03	15	2.25	I
KN1	Cambrian	Black shale	5501	2.14	18	2.04	I
KP[c] (outcrop)	O_1	Black limestone		0.90	120	1.04	II
KP (outcrop)	O_1	Black shale		1.20	118	1.10	II
KP (outcrop)	Cambrian	Black shale		1.84	141	N/F	I
TD1	Cambrian	Dark grey argillaceous limestone	4154	1.04	11	2.10	I
TD1	Cambrian	Dark grey argillaceous limestone	4360	2.31	10	2.16	I

[a] EVRo: Equivalent vitrinite reflectance based on the measured reflectance values of marine vitrinite and bitumen.
[b] The kerogen type was based on maceral analysis results of source rocks.
[c] KP: Keping.

into the Tazhong Uplift and the North Slope, and bordered it with the Manjiaer Depression (Fig. 1). This area obviously experienced several tectonic events, but only Palaeozoic events, characterized by not only subsidance and uplift, but also a strong compressional phase in the north–south direction, have had a significant impact on the formation and evolution of oil and gas pools (Duan, Xu & Wu, 1998; Jia, 1999; Liang, 1999; Tang, 1997; Tong, 1992; Wang, 1992; Zhang, 1992). Two tectonic events are recognised during the early and later Palaeozoic which are called the late Caledonian event and the early Hercynian event, respectively, by Chinese geologists (Din & Yun, 1992; Jia, 1999; Liang, Wang, Zhong & Liu, 1998; Wang, 1992; Zhang, 1992). Most of the faults, including the No. 1 fault in the Tazhong area were formed during the late Silurian, and middle to lower Silurian strata were eroded to different extents in the Tazhong area (Din & Yun, 1992). The compressional phase took place late in the Devonian during the later Palaeozoic event and led to the reactivation of some faults, eroding all of the Middle and Lower Devonian strata, and even some Silurian–Ordovician strata in the Tazhong Uplift. The Tazhong palaeo-uplift was formed during the first event and reservoirs formed during the early Palaeozoic were destroyed during the later event. Faults and unconformity surfaces formed during the two periods of tectonism provided the main pathways for hydrocarbon migration (Liang, 1999; Mei, 1998; Xiao & Liu, 1998; Xiao et al., 1996).

3. Petroleum System

3.1. Source rocks

There are two source areas and three sets of hydrocarbon source rocks in the Tazhong petroleum system. The North Slope contains Ordovician source rocks (Hao et al., 1996; Huang, 1994; Xiao, 1994; Xiao & Liu, 1998) developed mainly in middle and upper Ordovician strata. The analytical data for some typical core samples are presented in Table 1. Because of the higher maturity and general lower TOC (total organic carbon) content of the Cambrian–Ordovician sediments in the Tarim Basin, a relatively low standard of definition for a source rock has been used. Mudstone (including argillaceous limestone) and limestone with TOC > 0.50% and 0.40%, respectively, are regarded as a significant source rocks in the Tarim Basin (Huang, 1994; Huang, Zhao & Zhang, 1999; Liang, 1999; Liang & Wang, 1992; Liang et al., 1998). According to this standard, all the North Slope Ordovician samples listed in Table 1 are source rocks, with a content of total organic carbon (TOC) ranging from 0.47 to 1.18% and a hydrogen index (HI) ranging from 41 to 162 mg/g. The hydrocarbon source matter is dominated by algae–amorphinite or its thermally altered product micrinite, with mainly type II and partly type I kerogens. According to measured reflectance values of bitumen and marine vitrinite, the source rocks are still in the peak to late stages of oil

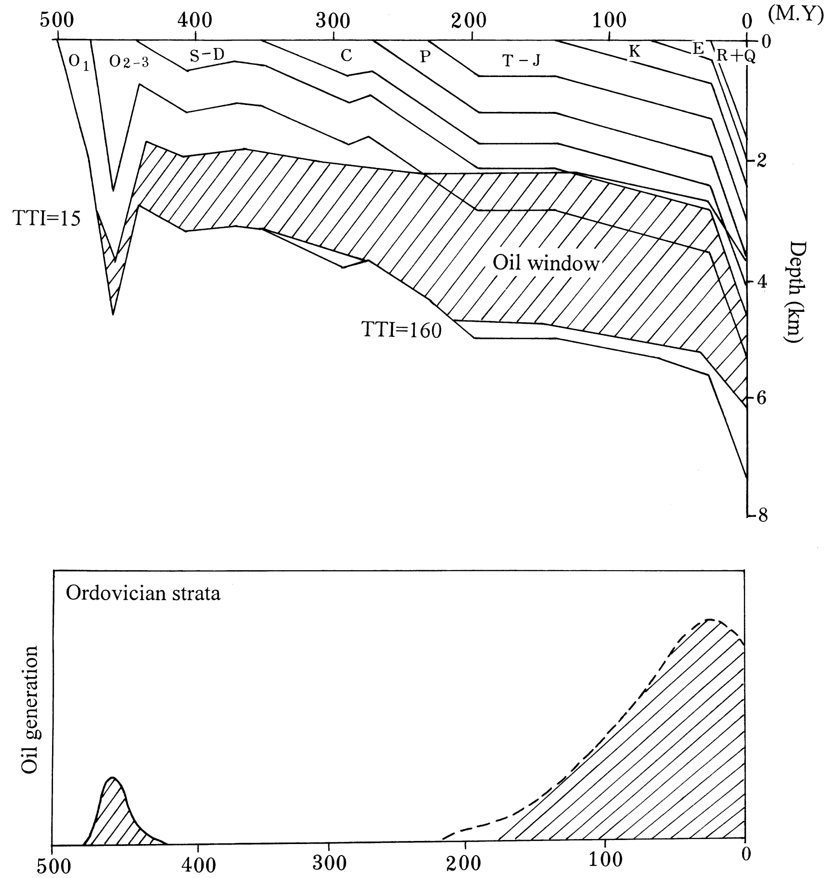

Fig. 4. Burial history and thermal maturation evolution of the Palaeozoic strata (top) at the well TZ12 in the North Slope, and a sketch map showing the oil generation trend of Ordovician strata (bottom). The TTI is computed by using Waples' method (Waples, 1980). The oil generation is not quantified.

generation, with an equivalent VRo (vitrinite reflectance) of 0.95–1.20% (Xiao & Liu, 1998). This set of source rocks is widely distributed over the whole North Slope with a cumulative thickness of 80–120 m and it has been confirmed to be one of major source rocks in the Tazhong petroleum system (Huang, 1994; Liang, 1999; Liang et. al., 1998; Xiao and Liu, 1998).

Another possible source area is the Manjiaer Depression where the existence of two sets of source rocks in the Cambrian and Ordovician have been postulated although there is no borehole which is deep enough to intersect the Cambrian–Ordovician strata in this area. Some data for the Cambrian and Ordovician source rocks from the surrounding areas of this depression are also shown in Table 1. The Cambrian strata in the Tazhong central uplift, the Tabei Uplift and the North Slope all contain a suite of black shale with TOC of 0.52–5.03%, while Ordovician source rocks consist of dark limestones and argillaceous limestones with TOC of 0.5–1.0%. According to seismic data and the distribution pattern of sedimentary facies, it is believed that the Cambrian–Ordovician strata in the Manjiaer Depression which was the deposition center of the Tarim Basin during the Cambrian and Ordovician periods should contain source rocks with a greater hydrocarbon potential than the source rocks in its surrounding areas. There is only one unpublished report that discusses the thickness of Cambrian (100–300 m) and Ordovician (300–500 m) source rocks in the Manjiaer Depression (Liu & Wen, 1998). Because of the great buried depth of Cambrian–Ordovician strata in the depression, these source rocks are all in the overmature stage. The investigation of oil-source correlation made by Huang (1994) and Liang et al. (1998) has shown that, in addition to the Ordovician source rock in the North Slope, there should be another oil source in Tazhong petroleum system and it is Cambrian–Ordovician source rocks in the southern part of the Manjiaer Depression.

In short, the huge volume of lower Palaeozoic source rocks in these two source areas must have supplied an important quantity of oil and gas to the Tazhong petroleum system.

3.2. Petroleum-generating history

From the burial and palaeotemperature history, the history of petroleum generation from the Cambrian–

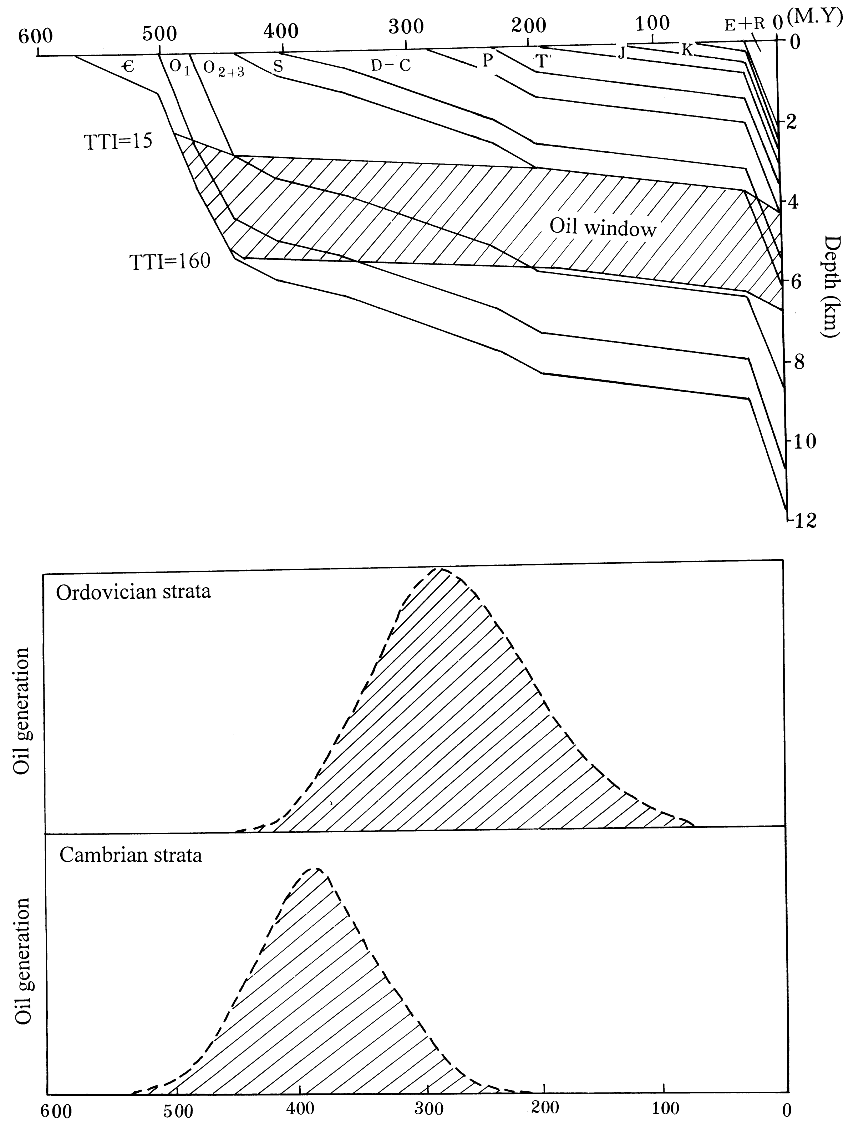

Fig. 5. Burial history and thermal maturation evolution of the Early Palaeozoic strata (top) at the well MC1 in the Manjiaer Depression, and a sketch map showing oil generation trend of Cambrian–Ordovician strata (bottom). The TTI is computed by using Waples' method (Waples, 1980). The oil generation is not quantified.

Ordovician source rocks for the well TZ12 in the North Slope and the well MC1 for the Manjiaer Depression have been simulated using Waples' method (Waples, 1980). The results (Fig. 4) show that petroleum generation from the lower part of the Ordovician strata began from the middle Ordovician, but stopped during uplift of this area in the late Ordovician. The Ordovician source rocks regenerated petroleum in the Late Cretaceous and matured to the peak stage of oil generation in the Tertiary. The Manjiaer Depression has been regarded as a continuously developing depression during geological history although a few unconformity surfaces have been recognized (Jia, 1999; Liang et al., 1998; Xiao & Liu, 1998). Fig. 5 shows that the main stage for oil generation was from middle Silurian to Early Devonian for the Cambrian strata, and from late Carboniferous to Late Permian for the Ordovician strata. Thus, there are three periods of petroleum generation in the Tazhong petroleum system — middle Silurian to Early Devonian, late Carboniferous to Late Permian, and Tertiary. Since the Tazhong area was uplifted during the early Palaeozoic, the hydrocarbons generated during all three periods could migrate toward this area to form oil and gas pools in suitable structures.

3.3. Combinations of reservoir-cap rocks

Three sets of combinations of reservoir-cap rocks have been confirmed in the Tazhong petroleum system. They are:

1. Lower Silurian interbedded sandstone and mud-

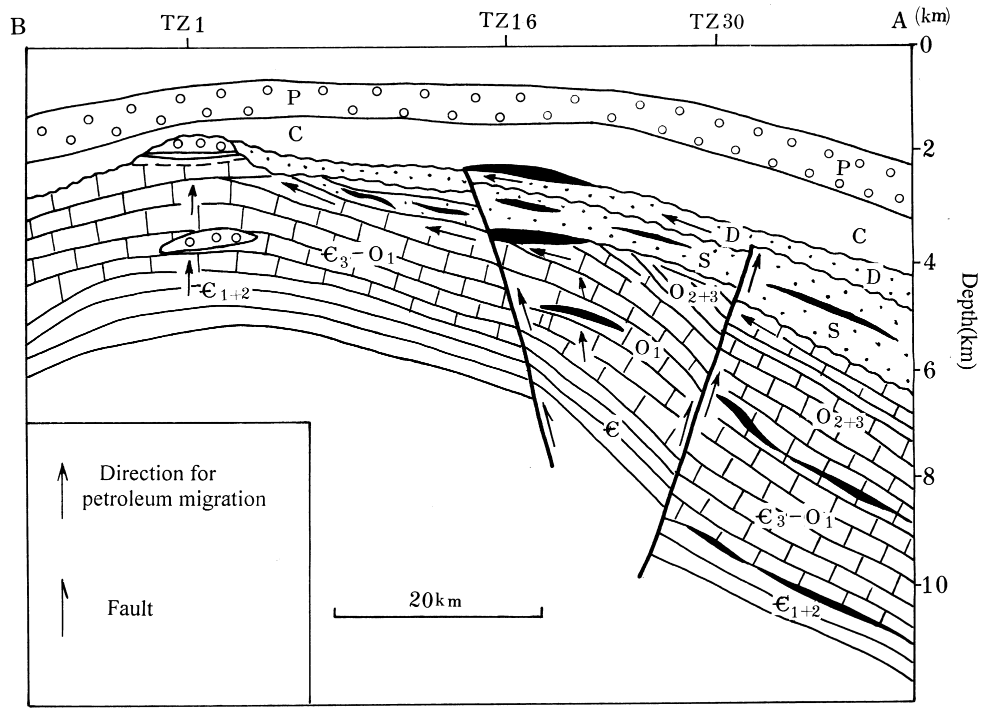

Fig. 6. Map showing the migration of hydrocarbon in the Tazhong petroleum system. Crushed fault belts and uncomformity surfaces form the interconnected pathways for hydrocarbon migration. Some of the faults cut through the Palaeozoic strata and provided the pathways for the mixture of hydrocarbons from different sources. The location of this section is shown in Fig. 1.

stone: The reservoir rock is a medium grained sandstone with a porosity 10–15% and a thickness of 50–100 m. The overlying rock is a widespread and well developed grey mudstone with a thickness of 10–20 m. These two sets of rocks found over the whole area of the North Slope form an excellent reservoir-cap combination. Because this lower Silurian sandstone generally contains some soft bitumen it has been called the 'bitumen sandstone' in the Tarim Basin (Huang, 1994; Liu, 1997; Xiao & Liu, 1998).

2. Lower Carboniferous interbedded sandstone and mudstone: This combination consists of three layers of sandstone interbedded with mudstone. The sandstone with a porosity of 15–20% is dominated by coarse to medium grains and it has a total thickness of 100–150 m. This combination is widely distributed over the Tazhong Uplift (Yan, 1992).
3. Ordovician carbonate reservoir-cap combination: Carbonate reservoirs with a porosity of 3–10% developed along palaeo-weathered layers of the lower Ordovician strata or surrounding successions and are characterized mainly by erosion pores and fissures. The overlying Carboniferous mudstone or the compact limestone itself formed the cap rocks of this combination (Yan, 1992).

Commercial oil and gas pools have been discovered in all three combinations of reservoir and cap rocks.

3.4. Trap structures

Anticlines are the main structural traps in the Tazhong petroleum system. Most current commercial oil and gas pools are associated with secondary anticline structures which are mostly related to faults. The

Table 2
Physical properties of some typical crude oils in the Tazhong petroleum system (Data after Xiao & Liu, 1998)

Sample	Well	Depth (m)	Reservoir	Types	Gravity (g/cm^3)	Wax (%)	Viscosity (mPa.s)	Sulphur (%)	NSO-compound (%)
1	TZ1	3563–3560	C–O_1	Light oil	0.7596	1.29	0.56	0.05	1.29
2	TZ4	3253–3277	C	Brown oil	0.8357	1.68	2.56	0.18	16.48
3	TZ4	3616–3669	C	Brown oil	0.8300	1.41	2.28	0.15	21.60
4	TZ10	4227–4235	S	Black oil	0.9086	6.93	780	0.61	31.25
5	TZ11	4294–4340	S	Black oil	0.9100	1.48	863	0.68	32.40

Table 3
Some geochemical parameters of some typical crude oils from Tazhong petroleum system[a]

Sample[b]	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	TT/H	HC_{30}/HC_{28}	H/S	$\delta^{13}C$ (‰)
1	1.05	0.29	0.28	2.04	0.94	1.43	−31.68
2	0.89	0.23	0.29	2.14	0.86	1.37	−32.98
3	0.91	0.20	0.21	0.11	3.08	0.90	−33.40
4	1.16	0.34	0.33	3.10	0.97	1.60	−32.84
5	1.01	0.32	0.31	3.18	0.94	1.55	−32.18

[a] TT, Tricylic terpane; H, Hopane; HC_{30}, Hopane C_{30}, HC_{28}, Hopane C_{28}, S, Sterane.
[b] The sample numbers are the same as in Table 2.

faults controlled the formation and evolution of the anticlines and the fault crush belts provided pathways for oil migrating into the reservoirs (Fig. 6).

3.5. Petroleum geochemistry

The crude oils found in the Tazhong petroleum system have the following features:

3.5.1. Physical properties

According to their physical properties, three types of crude oils are recognized in the Tazhong petroleum system (Table 2). The first type of crude oil was found in the oil and gas pool located within the Tazhong No.1 structure (TZ1 is the representative well for this structure). It is a light oil with a low density, a low wax content and a minor NSO fraction (no-hydrocarbon) and asphaltene. The second type of crude oil is represented by oil from the Tazhong No. 4 structure (TZ4 is one of the producing wells within this structure). It is a normal oil with a density of 0.83–0.85 g/cc^3, a moderate wax content and NSO fraction. A recently discovered heavy oil is another type of crude oil with a high density, NSO fraction and viscosity. A representative commercial reservoir is the lower Silurian sandstone of the Tazhong No.11 structure (the well TZ11 is located at the center of this structure).

In general, the light oil mainly occurs in the lower Silurian sandstone and lower Ordovician carbonate reservoirs, especially near unconformity surfaces. The heavy oil often co-exists with the lower Silurian bitumen sandstone, while the normal oil is mainly held in Carboniferous sandstone reservoirs.

3.5.2. Marine origin

Although the three types of crude oils have variable physical properties, their organic geochemical characteristics are largely similar, as indicated by the following parameters (Table 3):

1. Pristane predominance is not clear, with a Pr/Ph ratio of ca. 1.0.
2. Steranes are relatively abundant, with a hopane/sterane ratio ranging from 1.4 to 1.6.
3. High triterpane content, with a triterpane/hopane ratio ranging from 2.0 to -3.0.
4. Light carbon isotopic composition, with $\delta^{13}C$ lighter than −31.5‰.

All these features indicate that the crude oils are of marine origin, and generated from the Cambrian–Ordovician source rocks.

3.5.3. Thermal maturity variation

According to the index of diamantanes, asphaltene reflectance and maturity parameters of aromatics for the crude oils (Chen, Fu & Shang, 1996; Xiao & Liu, 1998; Xiao, Wilkins & Liu, 1998), the maturity of these three types of crude oils are quite different. The equivalent vitrinite reflectance values for the light oil, the normal oil and most of the heavy oil are 1.3–1.40%, 0.95–1.1% and 0.9–0.95%, respectively.

The maturity of a crude oil mainly depends on the maturity of its source rocks. Thus, it could be used to trace the origin of crude oils, combined with geological background information. The three types of crude oils in the Tazhong petroleum system characterized by different maturity imply that they were formed from different source areas and/or in different geological periods. However more work needs to be done to confirm this. The normal oil originated from the middle to upper Ordovician source rocks of the North Slope (Huang, 1994; Liang, 1999; Xiao, 1994; Xiao & Liu, 1998). On the basis of the present maturation levels of Cambrian and Ordovician source rocks in the Manjiaer Depression, it seems possible for both to have formed light oil, but only the period of oil generation from the Ordovician source rock enabled preservation. In any case it seems the light oil mostly originated from this set of source rocks. There are several possible explanations for the origin of the heavy oil, but the latest study on this region has shown that the heavy oil may be attributed to the alteration of soft bitumen in the lower Silurian sandstone by dilution with migrating light oil (Liang, 1999; Liu, 1997; Xiao & Liu, 1998).

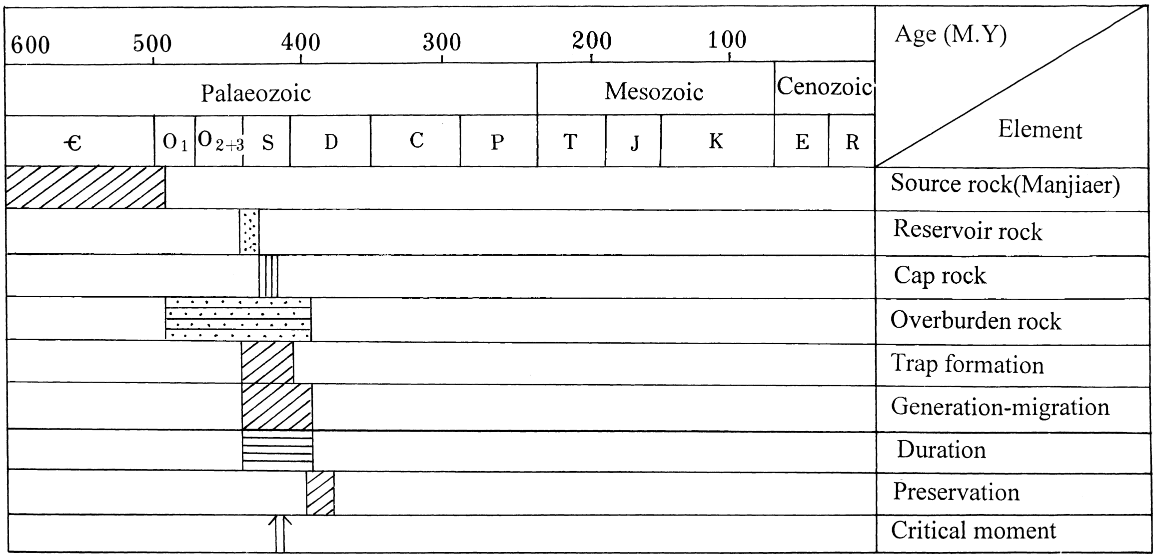

Fig. 7. Event chart of the Tazhong petroleum system during the Early Palaeozoic.

3.6. Petroleum migration

In the Lower Palaeozoic rocks of the Tazhong area, three phases of bitumen and organic fluid inclusions have been identified on the basis of their optical properties and occurrences (Xiao et al., 1996). The reflectance values of the three phases of bitumen are 1.30–2.8%, 0.5–0.70% and 0.1–0.3%. Corresponding to the bitumens there are three phases of organic fluid inclusions: pure liquid hydrocarbon inclusions with dark brown fluorescence, gaseous hydrocarbon inclusions with 20–30% liquid phase and green to blue fluorescence, and liquid hydrocarbon inclusions with 10–20% gaseous phase and yellow–green to yellow fluorescence. Bitumen and organic fluid inclusions are direct evidence of petroleum generation and migration. Xiao and Liu (1998) calculated the timing for the formation of the bitumen in the Tazhong area using an improved Karweil's method according to the burial and palaeotemperature histories. The results show that the first phase of bitumen formed during the middle Silurian, the second phase during the Permian and the third phase during the late Tertiary. Thus, the formation of the three phases of bitumen coincides spatially and temporally with the three main stages of petroleum generation from the three sets of Cambrian–Ordovician source rocks in the Tazhong petroleum system.

The major pathways for petroleum migration from source areas toward the Tazhong uplift are fault crushed belts and unconformity surfaces. The faults cut through the lower Palaeozoic strata and connected different sets of reservoir rocks, thus providing pathways for mixing of petroleum from different sources (Fig. 6).

3.7. Petroleum events

As described above, three sets of source rocks and three main periods for petroleum generation, migration and accumulation in the Tazhong petroleum system shows that three petroleum events occurred in this area.

3.7.1. Early Palaeozoic petroleum event

The major source rocks were of Cambrian age in the Manjiaer Depression. The main stage of oil generation occurred during middle Silurian to Early Devonian. The framework of the Tazhong Uplift was formed during the late Ordovician. The oil and gas migrated along the faults and unconformity surfaces into lower Silurian sandstone to form petroleum reservoirs in the Tazhong Uplift and the North Slope. Since strong uplift occurred in this area during the Late Devonian, the cap rocks were eroded and the reservoirs were breached and some of them were even destroyed. The wide occurrence of residual bitumen sandstone strata of early Silurian age in the Tazhong area is evidence for the existence of palaeo-oil and gas pools (Fig. 7).

3.7.2. Late Palaeozoic petroleum event

The major source rocks were Ordovician dark carbonates distributed in the Manjiaer Depression and the main stage for oil generation occurred during late Carboniferous–Permian. Because generation was from relatively mature source rocks in addition to a long migration pathway for the petroleum, large volumes of light oil were delivered to reservoirs to form oil pools dominated by the light oil. The migration pathways

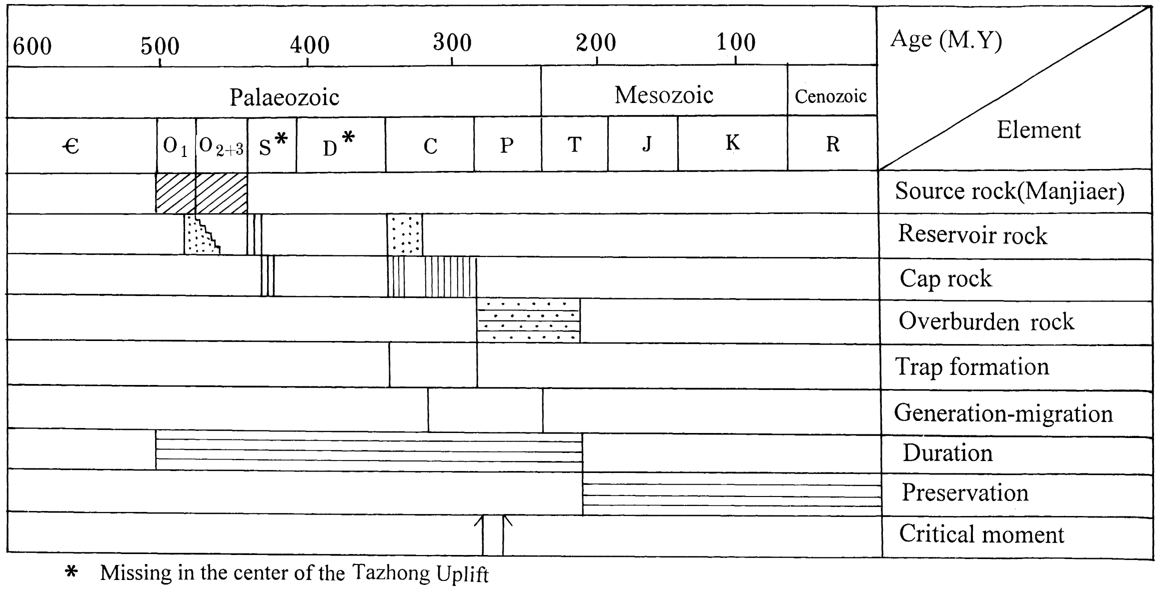

Fig. 8. Event chart of the Tazhong petroleum system during the late Palaeozoic.

were the crushed fault belts and unconformity surfaces. Currently, the oil and gas pools and structures formed during this petroleum event are confined to the lower Silurian sandstone and Ordovician carbonate reservoirs in close proximity to the unconformity surface between the Carboniferous and lower Ordovician strata. A typical example is the Tazhong No. 1 structural oil and gas pool (Liang, 1999; Xiao & Liu, 1998; Zhuo et al., 1997). As the light oil has diluted and altered the soft bitumen in the lower Silurian sandstone, heavy oil reservoirs could be formed in parts of a structure. For instance the lower Silurian sandstone reservoir in the Tazhong No. 11 structure produced commercial heavy oil (Fig. 8).

3.7.3. Cenozoic petroleum event

The major source rocks were Ordovician argillaceous limestones of the North Slope. Petroleum generation taking place mainly during the Tertiary from source rocks in the peak stage of oil generation produced mainly normal oil. The trap structures are mainly secondary anticlines related to faults in the Tazhong Uplift and the North Slope. The oil and gas generated during this event were able to migrate into

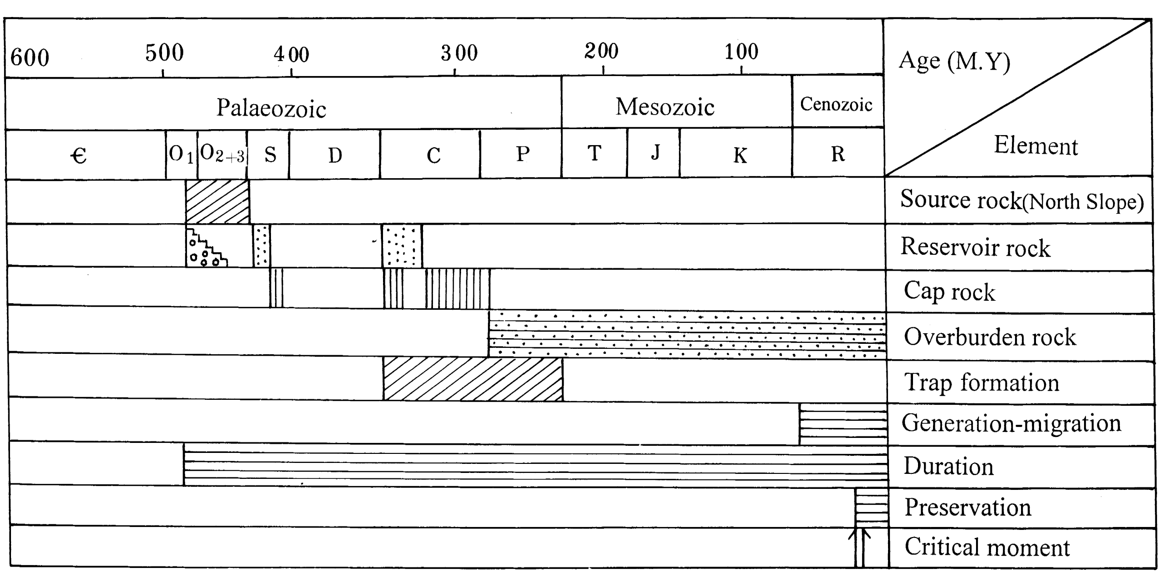

Fig. 9. Event chart of the Tazhong petroleum system during the Cenozoic.

all ages of reservoir rocks from Ordovician to Carboniferous along fault belts and unconformity surfaces. This has complicated the origin of oil and gas in the Tazhong petroleum system (Fig. 9). Representative oil and gas pools are the Carboniferous sandstone reservoirs in the Tazhong No. 4 structure (Huang, 1994; Liang, 1999; Xiao & Liu, 1998).

4. Conclusion

We have demonstrated the complexity of the Tazhong petroleum system. The features of this petroleum system are that there are several sets of source rocks formed in different geological periods and oil and gas were generated from them at different times. The oil and gas from different events co-existed or mixed in the same reservoir rocks. As the formation of an oil and gas pool is usually a result of multi-hydrocarbon events the origin of petroleum in any reservoir may be very complex. The Tazhong petroleum system is a typical example of a hybrid petroleum system. Such petroleum systems may be widespread in China's large to medium size superimposed petroleum basins and great attention should be paid to this possibility in the exploration of these basins.

Acknowledgements

The authors are indebted to Dr M. Allen and an anonymous reviewer for their constructive comments and suggestions on the original manuscript, to Professor D. G. Roberts for editing this paper, and to Dr R. W. T. Wilkins for improving the English. This paper has been supported by National Natural Science Foundation of China (NSFC Grant No. 49572194), and Chinese Academy of Sciences from the Program of Geochemical Problems in Petroleum System.

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