Control of hydrocarbon accumulation by Lower Paleozoic cap rocks in the Tazhong Low Rise, Central Uplift, Tarim Basin, West China

Zhang Yanping^{1, 2}, Lü Xiuxiang^{1, 2*}, Yang Haijun³, Han Jianfa³, Lan Xiaodong^{1, 2}, Zhao Yue³ and Zhang Jinhui⁴

¹ College of Geosciences, China University of Petroleum, Beijing 102249, China

² State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China

³ Tarim Oilfield Company, PetroChina, Korla, Xinjiang 841000, China

⁴ CNOOC Tianjin Branch Company, Tianjin 300452, China

© China University of Petroleum (Beijing) and Springer-Verlag Berlin Heidelberg 2014

Abstract: Despite the absence of regional cap rocks in the Lower Paleozoic for the entire Tazhong Low Rise, several sets of effective local cap rocks are well preserved on the Northern Slope. Of these the best is the Ordovician mudstone of the Sangtamu Formation; the second is the Silurian Red Mudstone Member of the Tatairtag Formation and the marl of the Ordovician Lianglitag Formation; and the third is the gray mudstone of the Silurian Kepingtag Formation. The dense limestone of the Ordovician Yingshan Formation and the gypsum of the Middle Cambrian have shown initial sealing capacity. These effective cap rocks are closely related to the distribution of Lower Palaeozoic hydrocarbons in the Tazhong Low Rise. With well-preserved Sangtamu Formation mudstone and its location close to migration pathways, rich Lower Paleozoic hydrocarbon accumulation can be found on the Northern Slope. Vertically, most of the reserves are distributed below the Sangtamu Formation mudstone; areally, hydrocarbons are mainly found in the areas with well-developed Sangtamu Formation mudstone and Lianglitag Formation marl. Burial history and hydrocarbon charging history show that the evolution of Lower Palaeozoic cap rocks controlled the accumulation of hydrocarbon in the Tazhong Low Rise. Take the Red Mudstone Member of the Tatairtag Formation and Sangtamu Formation mudstone for examples: 1) In the hydrocarbon charging time of the Late Caledonian – Early Hercynian, with top surfaces at burial depths of over 1,100 m, the cap rocks were able to seal oil and gas; 2) During the intense uplifting of the Devonian, the cap rocks with top surfaces at burial depths of 200-800 m and 500-1,100 m respectively were denuded in local areas, thus hydrocarbons trapped in earlier time were degraded to widespread bitumen; 3) In the hydrocarbon charging time of the Late Hercynian and Himalayan, the top surfaces of the cap rocks were at burial depths of over 2,000 m without intense uplifting and denudation thereafter, so trapped hydrocarbons were preserved. Based on cap rocks, the Ordovician Penglaiba Formation and Lower Cambrian dolomite could be potential targets for exploration on the Tazhong Northern Slope, and combined with hydrocarbon migration, less risk would be involved.

Key words: Cap rock, hydrocarbon accumulation, hydrocarbon destruction, Lower Paleozoic, Tazhong Low Rise

1 Introduction

Cap rocks play an important role in oil and gas preservation in hydrocarbon-bearing areas with strong tectonic activities. For instance, although the Papuan Fold & Thrust Belt of the Papua Basin experienced strong compression and deformation with plenty of seeps, over two billion barrels of recoverable oil equivalent were discovered;

the biggest Hides field had over 1,800 m gas column height, and the key is the sealing and plastic adjustment from Cretaceous mudstone cap rocks with around 1,000 m thickness (Hill, 1991; Hill et al, 2004). The Maracaibo Basin was located on the edge of plate convergence and experienced complex tectonic activities, with many oil seeps surrounding the basin. Still 44 billion barrels of recoverable oils were preserved, mainly owing to multiple sets of mudstone cap rocks (Escalona and Mann, 2006). The Kela 2 gas field, the most productive in China, is located in the highly deformed thrust belt of the Tarim Basin, and its formation is mainly due to high-quality Eocene evaporite regional cap rocks (Jia and

*Corresponding author. email: luxx@cup.edu.cn

Received December 6, 2012

Li, 2008).

The Tarim Basin, a typical superimposed basin with long-term evolution in west China, experienced multi-phase tectonic movements, multi-phase hydrocarbon expulsion (Gong et al, 2007; Zhang et al, 2011c; Tian et al, 2012), multi-phase oil & gas accumulation (Li et al, 1996; Jin and Wang, 2004; Meng et al, 2008; Pang et al, 2010), and multiple adjustment and destruction of hydrocarbon reservoirs (Lü et al, 1997). The Tazhong Low Rise is one of the petroliferous areas in the Tarim Basin, and experienced complex processes of hydrocarbon accumulation, adjustment and destruction (Jiang et al, 2008; Pang et al, 2013), thus research on cap rocks and preservation of hydrocarbons is important. However, the previous research on petroleum geology in the Tazhong Low Rise focused on source rocks and reservoir beds (Zhang et al, 2000; Li et al, 2009; Ding et al, 2012), and the Lower Palaeozoic cap rocks were less studied. In addition, the oil and gas discovered in the Tazhong Low Rise were mostly located in the Lower Palaeozoic, thus the relationship of hydrocarbon accumulation with the Lower Palaeozoic cap rocks can be instructive to exploration in the Tazhong Low Rise.

2 Geologic setting

2.1 Geologic structures in the Tazhong Low Rise

The Tazhong Low Rise with an area of 27,500 km² is located in the heartland of the Central Uplift of the Tarim Basin, and is adjacent to the Manjiaer Sag in the northeast with the Tazhong No.1 Fault as its border, the Awati Sag in the northwest, the Bachu Salient in the west with the Tumuxiuke Fault as borders, the Tangguzibasi Sag in the south and the Tadong Low Rise in the east (Fig. 1). Structural research shows that the Tazhong Low Rise with the eastern structure higher than the western one at present is a large complete NWW trending anticline structure with several secondary structural zones. From north to south, several fault belts were developed, namely the Tazhong No.1 Fault Belt, Tazhong No.10 Fault Belt, Tazhong No.2 Fault Belt, and the Tazhong Southern Fault Belt. In the plane, the fault systems spread to the west and converge to the east near the TZ5 well block (Fig. 1).

The Tazhong Low Rise is a pre-Carboniferous uplifted

Fig. 1 Geologic configuration of the Tazhong Low Rise

structure in the Paleozoic craton basin of the Tarim Basin. Tectonic activities on the southern basin margin played an important role in controlling the formation and development of Tazhong structures. According to stratigraphic development, structural deformation, unconformities and regional geology, the structural evolution in the Tazhong Low Rise can be divided into four stages (Jia, 1997): 1) Formation of rudimental structure (Sinian-Ordovician); 2) Thrust, strike-slip structural deformation and structural finalization (Silurian-Devonian); 3) Development of giant nose-shaped uplift (Carboniferous-Permian); 4) Stable subsidence and uplifting (Triassic-Quaternary).

2.2 Reservoir bed–seal combination in the Lower Paleozoic

The Silurian, Ordovician and Cambrian are developed in the Lower Paleozoic in the Tazhong Low Rise (Fig. 2).

In the Silurian, sandstones and mudstones were deposited in the Tatairtag Formation (S_2t) and Kepingtag Formation (S_1k). The lower member of S_2t is called Red Mudstone Member (S_2t-rmm) and is a premium cap rock for the Silurian oil and gas. The upper member of S_1k is further divided into 1st, 2nd and 3rd sub-members from top to bottom, the upper 2nd sub-member consists of gray mudstones and is called Gray Mudstone Sub-member (S_1k-gms) while the upper 1st and 3rd sub-members are both mainly composed of sandstone, thus the S_2t-rmm can seal the upper 1st sub-member of S_1k while the S_1k-gms can seal the upper 3rd sub-member of S_1k .

In the Ordovician, the Sangtamu Formation (O_3s) mainly consists of mudstone, while the underlying Lianglitag (O_3l), Yingshan (O_1y) and Penglaiba Formations (O_1p) mainly consist of carbonate rocks. O_3s is a premium cap rock for Ordovician hydrocarbons and direct cap rock for the hydrocarbons in O_3l limestones of reef-flat facies; the muddy limestone in the 3rd to 5th members of O_3l could be cap rock for the underlying weathering crust karst reservoir beds along the top part of O_1y ; the thick dense limestone without weathering and karstification in the O_1y is cap rock for underlying O_1p hydrocarbons.

In the Cambrian (ϵ) with upper dolomite member, gypsum member and lower dolomite member, the gypsum member can seal hydrocarbon in the lower dolomite member.

In the structural highs of the Tazhong Low Rise, the Carboniferous directly overlay the Ordovician (such as in the TZ2 well), and even the Cambrian (such as in the TZ1 well) as the result of strong denudation.

3 Features of Lower Paleozoic cap rocks

3.1 Red Mudstone Member in the Silurian (S_2t-rmm)

The S_2t-rmm mudstone is a set of cap rocks widely distributed in the Tazhong Low Rise, Manjiaer Sag and the southwest area of the Tabei Uplift.

The S_2t-rmm in the Tazhong Low Rise mainly consists of tidal flat facies brown mudstone, with an average total thickness of 70 m (29-109 m) and single layer thickness of 15-80 m. Areally, the S_2t-rmm mudstone gradually becomes thicker from southeast to northwest, but was completely

denuded at the east end of the Tazhong Low Rise and the Central Fault Horst Belt because of uplifting (Fig. 3). It is in sub-stage A of the middle diagenetic stage, because authigenetic clay minerals in the TZ23 well at 4,774 m near the bottom of S_2t-rmm are dominated by 75% illite-smectite (I/S), 15% illite and 10% kaolinite, and 20% smectite in I/S (S%) (Zhang et al, 2011c), and the Silurian vitrinite reflectance (R_o) is 0.9%-1.3%. Its breakthrough pressure ranges from 15.1 MPa to 25.1 MPa in four testing samples saturated with water (Wang et al, 2004).

3.2 Gray Mudstone Sub-member in the Silurian (S_1k-gms)

S_1k-gms in the Tazhong Low Rise is mainly composed of tidal flat facies gray mudstone, with an average total thickness of 18 m (8-35 m) and single layer thickness of 1-10 m, and thinner than the S_2t-rmm . Areally, S_1k-gms mudstone also gradually becomes thicker from south to north, but completely eroded at the east end of the Tazhong Low Rise and the Central Fault Horst Belt due to uplifting (Fig. 4).

It is also in sub-stage A of the middle diagenetic stage, because authigenetic clay minerals of the TZ37 well at 4,679.93 m near the bottom of S_1k-gms are dominated by 78% illite-smectite, 15% illite, 4% kaolinite and 3% chlorite, and 25% smectite in I/S (S%) (Zhang et al, 2011c). The breakthrough pressures are more than 15.1 MPa in all four testing samples saturated with water (Wang et al, 2004), thus it is able to seal the 3rd sub-member of S_1k (Lü et al, 2007).

3.3 Mudstone of Ordovician Sangtamu Formation (O_3s)

Previous research shows that the Lower Mudstone Member of the Carboniferous is a good regional cap rock in the Tarim Basin, which covers a giant hydrocarbon accumulation system. However, exploration progress shows that around 80% of oil and gas reserves accumulate below O_3s mudstone, thus it actually plays the most important role in sealing oil and gas in the Tazhong Low Rise.

During the deposition of O_3s with subsidence of the entire Tazhong area, the thick mudstone of shelf slope and deep water basin facies was deposited with an average total thickness of 570 m (100-1,100 m) and single layer thickness of 50-130 m. Areally, O_3s mudstone gradually becomes thicker from the Central Fault Horst Belt to both sides with broad lateral distribution, but completely denuded in the Central Fault Horst Belt and the east end of the Tazhong Low Rise due to uplifting (Fig. 5). The displacement pressures of O_3s mudstone range from 6.7 MPa to 37.1 MPa with an average of 15.3 MPa (Zhu et al, 2003).

According to statistics from 114 wells in the Tazhong Low Rise, the bottom depth of O_3s ranges from 3,825 m to 6,830 m with an average of 5,200 m; the 3,682-4,500 m of O_3s in the TZ28 well has R_o values of 1.03%-1.32%; the 5,415-5,420 m of O_3s in the TZ35 well has the T_{max} of 445-455 °C, while the 4,917-5,101 m of TZ10 well has the T_{max} of 428-443 °C. The clay minerals of Zhong13 well at 5,219 m in the O_3s are dominated by 78% illite, 5% kaolinite, 15% chlorite and 2% illite-smectite (I/S), and 15% (S%) in I/S (Qian et al, 2012).

Fig. 2 Stratigraphic column showing Lower Paleozoic reservoir bed-seal combination in the Tazhong Low Rise

O₃s in most areas of the Tazhong Low Rise is in sub-stage A₂ of the late diagenetic stage.

3.4 Marl of Ordovician Lianglitag Formation (O₃l)

O₃s mudstone is the direct cap rock for oil and gas in the underlying O₃l. In addition, hydrocarbon accumulation in reservoir beds of weathering crust karst was discovered in O₁y below O₃l. However, O₁y in most parts of the Tazhong Low Rise is far below O₃s mudstone at more than a few hundred meters, thus dense marl in the 3rd to 5th members of O₃l directly seals the hydrocarbons in O₁y.

The dense marl in the 3rd to 5th members of O₃l is a set of reef-flat complex sediments on a carbonate platform-shelf margin with an average total thickness of 220 m (100-400 m) and single layer thickness of 5-80 m. Areally, it gradually becomes thicker from the Central Fault Horst Belt to both sides with wide lateral distribution, but thinner in the ZG15-ZG24 well blocks with the 4th and 5th members of O₃l missing. In addition, it was also completely eroded in the Central Fault Horst Belt and the east end of the Tazhong Low Rise due to uplifting (Fig. 6). According to testing of dense marl cap rocks in 13 wells, no breakthrough occurred in 85%

Fig. 3 Mudstones isopach map of S_2t-rmm

Fig. 4 Mudstones isopach map of S_1k-gms

of samples after 48 hours under 14 MPa applied maximum pressure, while the two remaining samples respectively had the breakthrough pressure of 7 MPa and 10 MPa (Table 1).

According to statistics from 38 wells in the Tazhong Low Rise, the bottom depth of O_3l ranges from 4,033 m to 7,102 m with an average of 5,474 m. The homogenization temperatures of hydrocarbon inclusions range from 67 °C to 125 °C in the 3,976-6,099 m of O_3l from the TZ6, TZ12, TZ45 wells (Chen et al, 2010). According to PVT reports of 28 wells in the Tazhong Low Rise, the current formation temperatures of the 4,387-6,500 m in O_3l range from 126 °C to 151 °C with an average of 139 °C. The vitrinite reflectance

equivalent (VRE) values of O_3l range from 0.8% to 1.3% in the Zhong12, Zhong13, TZ10, TZ12 wells (Wang et al, 2001). O_3l in most areas of the Tazhong Low Rise is in sub-stage A_2 of the middle diagenetic stage, while in a few areas with deeper burial it entered sub-stage B of the middle diagenetic stage.

Thus the dense marl from the 3rd to 5th members of O_3l can seal the underlying hydrocarbons of O_1y .

3.5 Dense limestone of Ordovician Yingshan Formation (O_1y)

A large amount of drilling and seismic reservoir prediction

Fig. 5 O_{3s} mudstone isopach map with oil and gas in O_{3l}

Fig. 6 Dense marl isopach map of the 3rd to 5th members of O₃l with oil and gas in O₁y

from Tazhong No.2 Fault to Tazhong No.1 Fault (Fig. 7). For instance, in the TZ162 well near the Tazhong No.1 Fault O_{1y} has a thickness of 703 m, while in the TZ75 well near the Tazhong No.2 Fault O_{1y} thins to 202 m. Thus the northeast part of the Tazhong Northern Slope has thicker limestone in O_{1y} without weathering and karstification, where the hydrocarbons of O_{1p} could be better sealed.

O_{1V} consists of limestone, micrite and dolomite of open platform facies, but the relevant characteristics of the dense limestone cap rock cannot be evaluated currently, because there are few wells penetrating through O_{1V}.

Table 1 Breakthrough pressure of dense marl cap rock in the 3rd to 5th members of O₃l

Well	Depth, m	O ₃ l	Breakthrough pressure, MPa (Pressuring range: 0-14 MPa)
TZ12	4973.1	4 th member	No breakthrough after 48 hours under the max pressure
TZ162	4598.6	4 th member	No breakthrough after 48 hours under the max pressure
TZ27	4573.2	5 th member	No breakthrough after 48 hours under the max pressure
TZ35	5775.4	3 rd member	No breakthrough after 48 hours under the max pressure
TZ43	4647.4	5 th member	No breakthrough after 48 hours under the max pressure
TZ80	5423.2	5 th member	No breakthrough after 48 hours under the max pressure
TZ822	5808.4	3 rd member	No breakthrough after 48 hours under the max pressure
TZ825	5499.1	5 th member	No breakthrough after 48 hours under the max pressure
TZ83	5468.1	4 th member	No breakthrough after 48 hours under the max pressure
ZG8	6745.1	3 rd member	No breakthrough after 48 hours under the max pressure
ZG31	4133.0	3 rd member	No breakthrough after 48 hours under the max pressure
ZG19	6601.7	3 rd member	7
TZ63	6153.9	3 rd member	10

Notes: Above testing was completed by the laboratory of Langfang Branch, Research Institute of Petroleum Exploration and Development, CNPC

Fig. 7 Distribution of the Middle-Lower Ordovician on the Tazhong Northern Slope (see Fig. 6 for location)

3.6 Gypsum member of the Cambrian

The Middle Cambrian gypsum member acts as a good regional cap rock in the central-west area of the Tarim Basin, and was penetrated in the Tazhong Low Rise and Bachu Salient. In the Bachu Salient, gypsum-salt rocks of evaporite lagoon facies with a thickness of over 350 m developed at 3,822-4,379 m of the Fang-1 well and at 5,104-5,792 m of the He-4 well. In the Tazhong Low Rise, only the TC1 well penetrated through the Cambrian in the east of the Tazhong Low Rise, and the Middle Cambrian at 6,958-7,058 m is mainly composed of gypseous dolomite, dolomitic gypsum,

dolomite and thin bedded gypsum, with no salt rock.

Seismic data (Tang et al, 2012) and the TC1 well data indicate that the Middle Cambrian gypsum member is preserved in the Central Fault Horst Belt and the east end of the Tazhong Low Rise where the Lower Palaeozoic was denuded, thus the gypsum member might be present in the entire Tazhong Low Rise and becomes better cap rock from east to west according to sedimentary characteristics (Zhang et al, 2012).

3.7 Evaluation of cap rocks in the Tazhong Low Rise

The macroscopic and microscopic evaluation criteria of cap rocks in the Tazhong Low Rise are summed up according to previous research (Table 2). Based on characteristics of Lower Palaeozoic cap rocks in the Tazhong Low Rise, the best cap rock is the O₃s mudstone; secondly, the mudstone of S₂t-rmm and the marl in the 3rd to 5th members of O₃l; lastly, the S₁k-gms mudstone. The dense limestone of O₁y and the gypsum member of Middle Cambrian (E₂) preliminarily show sealing capacity and their regional distribution is waiting for further study (Table 3).

4 Relationship of hydrocarbon accumulation and Lower Paleozoic cap rocks

In the Tazhong Low Rise, commercial oil and gas flows have been discovered in the sandstone reservoir beds of S₁k,

Table 2 Macroscopic evaluation criteria of cap rocks in the Tazhong Low Rise (modified from Zhu et al, 2003)

Evaluation parameters		Classification of cap rocks			
		Class 1	Class 2	Class 3	Class 4
Macroscopic parameter	Sedimentary environment	Semi-deep-deep lake facies, basinal facies, open sea shelf facies	Platform facies lagoonal facies, inshore shallow lake facies, delta front sub-facies	Platform margin facies, littoral facies, delta distributary plain sub-facies	Fluvial facies, alluvial fan facies
	Lithology	Gypsum-salt rock mudstone, calcareous mudstone	Mudstone containing sand, mudstone containing silt	Silty mudstone, sandy mudstone, marl	Argillaceous siltstone, argillaceous sandstone
	Diagenetic stage	Sub-stage A of the middle diagenetic stage	Sub-stage B of the early diagenetic stage	Sub-stage B of the middle diagenetic stage sub-stage A of the early diagenetic stage	Late diagenetic stage
	Single layer thickness, m	>20	10-20	2.5-10	<2.5
	Cumulative thickness, m	>300	150-300	50-150	<50
Microscopic parameter	Breakthrough pressure, MPa	>15	15-10	10-5	<5

Table 3 Evaluation of Lower Palaeozoic cap rocks

Location of cap rocks	Macroscopic feature of cap rocks	Microscopic feature of cap rocks	Evaluation
Mudstone in S_2t-rmm	Mudstone of tidal flat facies, with cumulative thickness of 29-109 m and an average of 70 m, single layer thickness of 15-80 m, in sub-stage A of the middle diagenetic stage	With breakthrough pressure of 15.1-25.1 MPa	Macro: Class 2-3 Micro: Class 1
Mudstone in S_1k-gms	Mudstone of tidal flat facies, with cumulative thickness of 8-35 m and an average of 18 m, single layer thickness of 1-10 m, in sub-stage A of the middle diagenetic stage	With breakthrough pressure of more than 15.1 MPa	Macro: Class 3 Micro: Class 1
Mudstone in O_3s	Mudstone of shelf slope facies and deep water basin facies, with a thickness of 100-1,100 m and an average of 570 m, single layer thickness of 50-130 m, in sub-stage A_2 of the middle diagenetic stage	With displacement pressure of 6.7-37.1 MPa and an average of 15.3 MPa	Macro: Class 1 Micro: Class 1
Marl in O_3l	Reef-flat complex limestone of platform margin and shelf margin facies, with cumulative thickness of 100-400 m and an average of 220 m, single layer thickness of 5-80 m, in the sub-stage A_2 of the middle diagenetic stage	No breakthrough in 85% of samples after 48 hours under 14 MPa max applied pressure	Macro: Class 2-3 Micro: Class 2
Dense limestone in O_1y	Limestone and marl of open platform facies, with cumulative thickness of 400 m in TZ162 well	No data	No evaluation
Gypsum in ϵ_2	Gypsum member in TC1 well at the east end of the Tazhong Low Rise developed in evaporite lagoon facies with thickness of 100 m	No data	No evaluation

the reef-flat complex reservoir beds of O_3l , the weathering crust karst reservoir beds of O_1y and the carbonate karst reservoir beds of O_1p . Around 80% of reserves in the Tazhong Low Rise are found in O_3l and O_1y below O_3s mudstone cap rocks.

Previous research shows that there were at least three periods of large-scale hydrocarbon accumulation, including Late Caledonian–Early Hercynian, Late Hercynian, and

Himalayan (Zhang et al, 2011a; Pang et al, 2013).

4.1 Hydrocarbon accumulation versus Silurian mudstone cap rock

Dry bitumen, asphalt, heavy oil and light oil coexist in the upper 1st and 3rd sub-members of S_1k below S_2t-rmm , indicating that the sub-members experienced multiple phases of hydrocarbon charging and complex processes of

accumulation and loss.

Bitumen is widely distributed in the upper 1st and 3rd sub-members of S_1k in the Tazhong Low Rise (Fig. 3). It was formed from hydrocarbons charged in the Late Caledonian – Early Hercynian but degraded by Devonian uplifting (Zhang et al, 2004; 2011c). Almost all the Silurian bituminous sandstones are distributed below the S_2t-rmm cap rock, but there is no bitumen in the Silurian sandstone above the Red Mudstone Member cap rock except four wells including TZ10 well due to connection of faults (Zhang et al, 2004). This indicates that S_2t-rmm cap rock possessed sealing capacity during the early period of hydrocarbon charging and controlled the vertical distribution of hydrocarbons.

In the Silurian in the Tazhong Low Rise, there are five oil and gas reservoirs (Fig. 3), all in the upper 1st and 3rd sub-members of S_1k below S_2t-rmm cap rock, while there is no hydrocarbon accumulation in Silurian sandstones above S_2t-rmm cap rock (Fig. 8). This indicates that cap rock from S_2t-rmm still controlled vertical distribution of Silurian hydrocarbons charged in late periods. In addition, Silurian movable oil is mainly found in the upper 3rd sub-member of S_1k below the direct cap rock from S_1k-gms , because the upper 3rd sub-member of S_1k is the oil-bearing formation of the five reservoirs. By comparison, the upper 1st sub-member of S_1k is the oil-bearing formation of only two reservoirs. The reservoir bed quality of the upper 3rd sub-member of S_1k is better than the upper 1st sub-member of S_1k . Meanwhile, the direct cap rock of the upper 3rd sub-member of S_1k , that is S_1k-gms possessed sealing capacity during the late period of hydrocarbon charging.

4.2 Hydrocarbon accumulation versus O_3s mudstone cap rock

Ordovician oil and gas exploration is mainly on the

Tazhong Northern Slope. There is a large oil and gas accumulation in O_3l with a superimposed petroliferous area of over 1,000 km² including natural gas, condensate and normal crude oil, whose principal payzones are limestone reservoir beds of the 1st to 3rd members of O_3l reef-flat complex of platform margin facies, while its direct cap rock is the O_3s mudstone. Meanwhile, the O_3s mudstone also plays the role of local cap rock in the Tazhong Low Rise, thus about 80% of Tazhong Low Rise's reserves are concentrated below O_3s .

The locations of O_3l hydrocarbon reservoirs correspond well with areas of thick O_3s mudstone. That is to say, firstly, hydrocarbons accumulate in the area where the mudstone cap rocks have a thickness of more than 300 m (Fig. 5); secondly, the thinner the mudstone cap rocks from northeast to southwest, the more the low productivity wells (such as the TZ15 well) and hydrocarbon show wells (such as the TZ23 and the TZ42 well) were drilled. In addition, on the top and both sides of the Central Fault Horst Belt with missing mudstone cap rocks, a number of dry wells and a few wells with only hydrocarbon shows were drilled. Therefore, the abundance of O_3l hydrocarbons correlates with the thickness of overlying mudstone, although source rock, structural configuration, migration and reservoir bed quality are also factors influencing hydrocarbon distribution. It is a consensus that the sealing of thick O_3s mudstone controlled regional distribution of underlying oil and gas.

4.3 Hydrocarbon accumulation versus O_3l marl cap rock

In the Tazhong Low Rise, the weathering crust karst carbonate oil and gas reservoirs in O_1y have a superimposed petroliferous area of 3,000 km² (Fig. 6). The marl of the 1st to 3rd members of O_3l acts as cap rock for underlying O_1y , and also controls hydrocarbon accumulation in O_1y .

Fig. 8 Distribution profile of bituminous sandstone, movable oil and cap rock of the Silurian (see Fig. 3 for location)

Bitumen and heavy oil are widespread in O_{1y} in the Central Fault Horst Belt, Tazhong Low Rise, where nearly 20 wells were drilled targeting carbonate buried hills of O_{1y} and encountered widespread bitumen and heavy oil in weathering crust reservoir beds (Table 4). The area experienced Devonian uplifting, which led to erosion of the entire Middle

and Upper Ordovician as well as part of Lower Ordovician. From then on, this area did not subside and receive sediment until the Carboniferous with the absence of marl cap rock in the 3rd to 5th members of O_3l (Fig. 6). Hence large-scale uplifting resulted in destruction of O_{1y} hydrocarbons charged in the earlier period (Lü et al, 2004; Zhang et al, 2011b).

Table 4 Oil and gas shows in the Central Faulted Horst Belt, Tazhong Low Rise

Well	Top depth of weathering crust (O_1), m	Depth of coring interval, m	Core thickness, m	Fracture-cavity and oil and gas show
TZ2	3883.0	3872.2 - 3903.5	3.1	Fissures developed and half-filled with asphalt. Small and medium holes developed with heavy crude outflow
TC1	4295.0	5065.8 - 5113.2	43.86	Fissures developed, partly filled or half-filled with coaly asphalt. Holes developed with light crude outflow partly
TZ17	4116.0	4116.0 - 4143.6	27.6	Fissures and holes developed, filled or half-filled with asphalt. Holes filled with asphalt
TZ61	3973.0	3975.0 - 3983.4	8.4	Fissures developed, filled or half-filled with asphalt. Holes developed, partly filled with asphalt

The discovered oil and gas in O_{1y} is concentrated on the Tazhong Northern Slope. In addition to reservoir bed development and hydrocarbon migration, the O_3l marl cap rock is also an important factor. According to updated exploration data, oil and gas of O_{1y} are concentrated in the area with a marl thickness of more than 100 m, and the thicker the marl, the higher the gas/oil ratio (Fig. 6). Therefore, for the Tazhong Northern Slope with multiple phase hydrocarbon charging, earlier oil charging and later gas charging, the quality of cap rock is one of the factors determining gas/oil ratio in oil and gas bearing formations.

There is a difference in the development characteristics of the marl cap rock in O_3l between the west and east of the Tazhong Northern Slope.

In the west of the Tazhong Northern Slope, there are no 4th and 5th members of O_3l , thus cap rock quality of marl in the 3rd member of O_3l controls the vertical distribution of underlying hydrocarbons (Fig. 9). That is to say, to the west of ZG15 well, hydrocarbons could not accumulate in O_{1y} below the 3rd member of O_3l but migrated upward to the 2nd and 3rd members of O_3l , due to poor marl cap rock quality in the 3rd member of O_3l with relatively low natural gamma, low shale content and low breakthrough pressure (there was a breakthrough in the sample of ZG19 well under the pressure of 7 MPa). While to the east of ZG15 well, hydrocarbons almost all accumulated in O_{1y} below the 3rd member of O_3l , due to good cap rock quality of marl in the 3rd member of O_3l with relatively higher natural gamma, higher shale content and higher breakthrough pressure (there was no breakthrough after 2 days in the sample of ZG8 well under the maximum pressure of 14 MPa).

In the east of the Tazhong Northern Slope, the marl cap rock in the 3rd to 5th members of O_3l has a thickness of more than 200 m, meanwhile, there was no breakthrough after 2 days during breakthrough pressure testing of core samples from 8 wells under the maximum pressure of 14 MPa (Table 1). This indicates that marl cap rock in the 3rd to 5th members

of O_3l could seal the underlying hydrocarbons of O_{1y} to form sizable O_{1y} oil and gas accumulation.

4.4 Hydrocarbon accumulation versus O_{1y} dense limestone cap rock

There is thick bedded dolomite with a thickness of around 700 m in O_{1p} in the Tazhong Low Rise. Seismic profiles show obvious “string of beads” shaped seismic reflections along the top surface of O_{1p} which represent the reflections of karst caves, vugs and fractures (Yuan et al, 2012). The overlying dense limestones without weathering in O_{1y} act as cap rock for O_{1p} . The cap rock becomes thicker in the northeast part of the Tazhong Northern Slope near the Tazhong No.1 Fault, thus this area is favorable for exploration for O_{1p} hydrocarbon.

Taking the TZ162 well as an example, with a top unconformity depth of O_{1y} at 4,900 m, the depth of the karst reservoir bed controlled by the unconformity is 5,120 m from log interpretation; meanwhile, the depth of O_{1y} bottom bed boundary with underlying O_{1p} is 5,603 m, thus the dense limestone section from 5,120 m to 5,603 m in O_{1y} with a thickness of 483 m could act as cap rock for underlying O_{1p} . In O_{1p} , acidizing testing for 5,931-6,050 m with a 9 mm nozzle produced 183,880 m³ of gas. Therefore, the karst reservoir bed in O_{1p} and the dense limestone section without weathering in O_{1y} could form a good reservoir bed–cap combination.

4.5 Hydrocarbon accumulation versus Cambrian gypsum cap rock

There are high quality source rocks with a high abundance of organic matter in the Middle and Lower Cambrian around the Tazhong Low Rise. Meanwhile, the structures and dolomite reservoir beds below the Middle Cambrian gypsum cap rock are relatively well developed. Seismic data show

Fig. 9 Development characteristics of O_{3I} cap rocks versus location of payzones on the Tazhong Northern Slope

that the Middle and Lower Cambrian salt-related structures are distributed in rows or belts along basement faults or fault-block belts in the Tazhong Low Rise (Tang et al, 2012).

The TC1 well penetrated the finely crystalline and silt-sized crystalline dolomites in the 7,085-7,162 m of Lower Cambrian. In parts of the core, vugs and fractures are well developed and are mostly half-filled or filled with crystal-clustered dolomite, bitumen or shale, while the largest vertical fracture is 0.33 m long and 2 mm wide and the largest vug is 35×12 mm. There was no oil smell when out of core barrel and some air bubbles emerged along the fractures.

In the Tazhong Low Rise, only the TC1 well in the east area penetrated through the Middle Cambrian gypsum, but the cap rock quality of gypsum in the central-west area should be better than the east area according to sedimentary characteristics. If this is confirmed by drilling, most probably sizable oil and gas could have been accumulated in the Lower Cambrian dolomites below the Middle Cambrian gypsum member.

5 Control on hydrocarbon accumulation by cap rocks

The Tarim Basin experienced complex tectonic movements and multi-phase hydrocarbon charging, and hydrocarbon accumulations were formed in multiple sets of reservoir bed–cap combinations. Research on the control of hydrocarbon accumulation by the Lower Palaeozoic cap rocks has to be combined with tectonic evolution, history of hydrocarbon generation and expulsion and hydrocarbon

migration.

There are two sets of effective source rocks in the Cambrian-Lower Ordovician and the Middle-Upper Ordovician (Cai et al, 2009; Zhang et al, 2012). The Tazhong Low Rise experienced at least three periods of large-scale hydrocarbon accumulation: Late Caledonian–Early Hercynian, Late Hercynian and Himalayan (Zhang et al, 2011c; Pang et al, 2013).

The 1st period of large-scale hydrocarbon accumulation happened in the Late Caledonian – Early Hercynian, when the effective source rocks in Cambrian–Lower Ordovician of the Manjiaer Sag and Awati Sag adjacent to the north of the Tazhong Low Rise started large-scale hydrocarbon expulsion, and the Tazhong Low Rise was charged with hydrocarbon beginning from parts in the northwest and northeast (Zhang et al, 2011b). During the 1st period of hydrocarbon accumulation, S₂t-rmm cap rock developed with its top surface at a maximum burial depth of 1,150-1,350 m (Fig. 10(a)) and highest palaeo-geotemperature of around 60 °C (Fig. 10(c), 10(d)), at sub-stage A of the early diagenetic stage.

The ages of the authigenic illite of the Silurian bituminous sandstones in the wells of TZ11 and TZ47 respectively are 364 Ma and 384 Ma, Early Hercynian (Zhang et al, 2011c). This suggests that the widespread Silurian bitumen in the Tazhong Low Rise evolved from the hydrocarbon accumulated during the 1st period of hydrocarbon accumulation. Meanwhile, almost all the Silurian bituminous sandstones were distributed below the S₂t-rmm cap rock, suggesting that S₂t-rmm cap rock with sealing capacity controlled vertical distribution

of Silurian hydrocarbons (Zhang et al, 2004). In addition, the O_3s mudstone cap rock also had sealing capacity at a top surface depth of 1,400–1,500 m (Fig. 10(b)).

Intense Devonian uplifting destroyed the hydrocarbons charged in the Late Caledonian–Early Hercynian. In the Central Fault Horst Belt and the east end area of the Tazhong Low Rise, the cap rocks including the mudstone of S_2t-rmm , the mudstone of O_3s and the marl of O_3l were completely denuded (Fig. 10(c), 10(d)). Meanwhile, in the remaining area of the Tazhong Low Rise, the cap rocks were preserved with S_2t-rmm mudstone at top surface depth of 200–800 m and O_3s mudstone at top surface depth of 500–1,100 m (Fig. 10(a), 10(b)). When the burial depth of oil reservoirs was less than 1,500 m, crude oil was prone to suffering water washing oxidation and biodegradation (Larter et al, 2003). Meanwhile, the main strike-slip fault activity of the Tazhong area was sustained in the Early Hercynian (Li et al, 2013), thus tectonic uplifting and fault cutting resulted in the destruction of the Lower Paleozoic hydrocarbon reservoirs which were charged in earlier periods forming bitumen in sandstones and carbonates.

The 2nd period of large-scale hydrocarbon accumulation

happened in the Late Hercynian. Permian volcanic activity resulted in a geothermal gradient of the Tarim Basin of up to 34–38 °C/km, thus the effective source rocks of Middle–Upper Ordovician in the west of the Manjiaer Sag started to expel oil at a large-scale then the hydrocarbon migrated into structural high areas along karstic carrier beds and unconformities from north to south and from northwest to southeast (Zhang et al, 2011b). During the 2nd period of hydrocarbon accumulation, S_2t-rmm and O_3s mudstone developed with a top surface burial depth of 2,100–2,500 m and 2,350–2,800 m respectively (Fig. 10(a), 10(b)), all more than 2,000 m. Thereafter, there was no cap rock destruction by uplifting and denudation (Fig. 10(c), 10(d)), thus the accumulated hydrocarbons were well preserved. In addition, Ordovician reservoir beds in the Tazhong Low Rise experienced long-term and widespread karstification with well-developed dissolution pores, thus providing good space for large-scale oil expulsion and charging. This is why the discovered commercial oils in the Tazhong Low Rise were mainly generated from the Middle–Upper Ordovician source rocks (Zhang et al, 2000; Li et al, 2010; Zhang et al, 2011b; Tian et al, 2012).

The 3rd period of large-scale hydrocarbon accumulation

Fig. 10 Top depth change diagram of S_2t-rmm and O_3s mudstone (attached with single well evolution diagrams of burial history and thermal history)

happened in the Himalayan. The Middle-Upper Ordovician effective source rocks in the slope area of the Tazhong Low Rise started to expel hydrocarbon, and the oil generated from the Cambrian-Lower Ordovician effective source rocks in earlier periods cracked into gas (Zhang et al, 2011b). Thus the accumulated Ordovician carbonate oil reservoirs were gradually altered by gas invasion from deep reservoirs, while the intersection of the Tazhong No.1 Fault with main strike slip faults acted as hydrocarbon charging points (Pang et al, 2013). On the Tazhong Northern Slope which was near the hydrocarbon charging points, the cap rocks of O_3s mudstone and O_3l marl were well preserved with relatively large thickness. In addition, during the 3rd period of hydrocarbon accumulation, S_2t-rmm and O_3s mudstone developed with top surface burial depths of 3,000-3,750 m and 3,500-4,000 m respectively (Fig. 10(a), 10(b)), thus sizable condensate reservoirs were formed in the Ordovician carbonate along the Tazhong Northern Slope.

In structural high areas of the Central Fault Horst Belt and the east end of the Tazhong Low Rise, the Lower Paleozoic cap rocks were denuded by Devonian uplifting after the 1st period of large-scale hydrocarbon accumulation, resulting in the absence of regional sealing for hydrocarbons migrating in late periods. Therefore, there is no important discovery in the Lower Paleozoic after drilling 20 wells in the study area.

In summary, oil and gas accumulated in the Lower Palaeozoic during the early period of hydrocarbon accumulation were destroyed or degraded due to shallow burial depth of cap rocks; while oil and gas accumulated during late periods of hydrocarbon accumulation have been preserved due to suitable burial depth of cap rocks. The Tazhong Northern Slope with relatively well-preserved Lower Palaeozoic cap rocks and its location near hydrocarbon migration pathways is rich in oil and gas; while the Central Fault Horst Belt and the east end of the Tazhong Low Rise suffered denudation of Silurian and Ordovician cap rocks, and no important discovery has been made in the Lower Palaeozoic.

6 Conclusions

1) Several sets of effective local cap rocks are well preserved on the Tazhong Northern Slope despite the lack of regional cap rock covering the entire Tazhong Low Rise. The best cap rock is the mudstone of O_3s ; the second is the mudstone of S_2t-rmm and the marl of O_3l ; the third is the mudstone of S_1k-gms . The dense limestone of O_4p and the gypsum of ϵ_2 show sealing capacity, but their regional distributions are waiting for confirmation by drilling.

2) The Lower Palaeozoic effective cap rocks are closely related to hydrocarbon accumulation in the Tazhong Low Rise. The Tazhong Northern Slope near migration pathways and with well-preserved cap rocks is rich in Lower Palaeozoic hydrocarbons. However, the Central Fault Horst Belt and the east end of the Tazhong Low Rise suffered denudation of multiple sets of cap rocks, thus no large-scale discovery of hydrocarbons in the Lower Palaeozoic has been made there. Areal, Ordovician hydrocarbons are distributed in the areas where cap rocks including O_3s mudstone and O_3l marl are

well-developed; vertically, most of reserves in the Tazhong Low Rise are distributed below O_3s mudstone cap rock, and almost all bituminous sandstones and movable oils from the Silurian are concentrated below S_2t-rmm mudstone cap rock.

3) The Tazhong Low Rise experienced three periods of large-scale hydrocarbon accumulation and complex tectonic movements, and the evolution of Lower Paleozoic cap rocks controlled hydrocarbon accumulation. Taking cap rocks of S_2t-rmm and O_3s mudstone as examples, in the Late Caledonian – Early Hercynian period of hydrocarbon charging, the cap rocks with top surface burial depths of 1,150-1,500 m could seal oil and gas; thereafter, with intense Devonian uplifting, the cap rocks with the top surface burial depths of 200-800 m and 500-1,100 m respectively were denuded in local areas, thus the hydrocarbons accumulated in earlier periods were degraded to widespread bitumen. In the Late Hercynian period of oil expulsion, the top surfaces of the cap rocks were at burial depths of 2,100-2,800 m and without denudation by uplifting thereafter, thus commercial oil accumulations were preserved. In the Himalayan period large-scale gas invasion occurred, and top surfaces of O_3s mudstone were at burial depths of 3,500-4,000 m and without denudation by uplifting thereafter, thus sizable condensate reservoirs of O_3l were formed.

4) The potential exploration targets in the Lower Paleozoic in the Tazhong Low Rise can be determined based on the characteristics of cap rocks. The first target is O_4p below O_4y dense limestone cap rock, because good dolomite reservoir beds developed in the top part of O_4p or along the faults and accumulation of hydrocarbons have been confirmed by drilling. The second target is the Lower Dolomite Member below the ϵ_2 gypsum cap rock, because the cap rock could be widespread in the entire Tazhong Low Rise, and salt-related structures and dolomite reservoir beds were relatively well developed. The regional distribution of gypsum cap rock is awaiting further confirmation. Combined with hydrocarbon migration, less risk would be involved in exploration on the Tazhong Northern Slope.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 41072102), National Key Basic Research Development Plan (“973” Project, No. 2005CB422108) and National Major Projects (Nos. 2008ZX05004-004, 2011ZX05005-001).

References

- Cai C F, Li K K, Ma A L, et al. Distinguishing Cambrian from Upper Ordovician source rocks: Evidence from sulfur isotopes and biomarkers in the Tarim Basin. *Organic Geochemistry*. 2009. 40(7): 755-768
- Chen R Y, Zhao W Z and Wang H J. Fluid inclusion evidence for charge stages of hydrocarbon in the Ordovician of Tazhong area, Tarim Basin. *Petroleum Exploration and Development*. 2010. 37(5): 537-542 (in Chinese)
- Ding W L, Fan T L, Yu B S, et al. Ordovician carbonate reservoir fracture characteristics and fracture distribution forecasting in the Tazhong area of Tarim Basin, Northwest China. *Journal of Petroleum*

- Science and Engineering. 2012. 86-87: 62-70
- Escalona A and Mann P. An overview of the petroleum system of Maracaibo Basin. AAPG Bulletin. 2006. 90(4): 657-678
- Gong S, George S C, Volk H, et al. Petroleum charge history in the Lunnan Low Uplift, Tarim Basin, China – Evidence from oil-bearing fluid inclusions. Organic Geochemistry. 2007. 38(8): 1341-1355
- Hill K C. Structure of the Papuan Fold Belt, Papua New Guinea. AAPG Bulletin. 1991. 75(5): 857-872
- Hill K C, Keetley J T, Kendrick R D, et al. Structure and hydrocarbon potential of the New Guinea Fold Belt. In: McClay K R (ed.), Thrust Tectonics and Hydrocarbon Systems: AAPG Memoir 82. Tulsa, Oklahoma: AAPG. 2004. 494-514
- Ji Y G, Han J F, Zhang Z H, et al. Formation and distribution of deep high quality reservoirs of Ordovician Yingshan Formation in the Northern Slope of the Tazhong area in Tarim Basin. Acta Geologica Sinica. 2012. 86(7): 1163-1174 (in Chinese)
- Jia C Z. Tectonic Characteristics and Petroleum, Tarim Basin, China. Beijing: Petroleum Industry Press. 1997. 279-283 (in Chinese)
- Jia C Z and Li Q M. Petroleum geology of Kela-2, the most productive gas field in China. Marine and Petroleum Geology. 2008. 25(4-5): 335-343
- Jiang Z X, Pang X Q, Liu L F, et al. Quantitative studies of hydrocarbon loss of the Silurian bitumen sandstone in the Tarim Basin. Science in China Series D: Earth Sciences. 2008. 51(S2): 101-107
- Jin Z J and Wang Q C. Recent developments in study of the typical superimposed basins and petroleum accumulation in China: Exemplified by the Tarim Basin. Science in China Series D: Earth Sciences. 2004. 47(S2): 1-15
- Larter S, Wilhelms A, Head I, et al. The controls on the composition of biodegraded oils in the deep subsurface—part 1: biodegradation rates in petroleum reservoirs. Organic Geochemistry. 2003. 34(4): 601-613
- Li C X, Wang X F, Li B L, et al. Paleozoic fault systems of the Tazhong Uplift, Tarim Basin, China. Marine and Petroleum Geology. 2013. 39(1): 48-58
- Li D S, Liang D G, Jia C Z, et al. Hydrocarbon accumulations in the Tarim Basin, China. AAPG Bulletin. 1996. 80(3): 1587-1603
- Li S M, Li M W, Pang X Q, et al. Origin of crude oils with unusually high dibenzothiophene concentrations in the Tazhong Uplift, Tarim Basin. Journal of Geochemical Exploration. 2009. 101(1): 60
- Li S M, Pang X Q, Jin Z J, et al. Petroleum source in the Tazhong Uplift, Tarim Basin: New insights from geochemical and fluid inclusion data. Organic Geochemistry. 2010. 41(6): 531-553
- Lü X X, Fan Q H, Zhao F Y, et al. The Silurian play in the Tazhong Uplift, Tarim Basin, northwestern China. Marine and Petroleum Geology. 2007. 24(3): 189-198
- Lü X X, Jin Z J, Liu L F, et al. Oil and gas accumulations in the Ordovician carbonates in the Tazhong Uplift of Tarim Basin, west China. Journal of Petroleum Science and Engineering. 2004. 41(1-3): 109-121
- Lü X X, Zhang Y W and Jin Z J. Reservoir formation cycle of Tarim Basin, NW China. Chinese Science Bulletin. 1997. 42(3): 245-248
- Meng Q Y, Pang X Q and Gao J B. The multi-factor recombination and processes superimposition model for hydrocarbon accumulation: application to the Silurian in the Tarim Basin. Petroleum Science. 2008. 5(1): 13-19
- Pang H, Chen J Q, Pang X Q, et al. Key factors controlling hydrocarbon accumulations in Ordovician carbonate reservoirs in the Tazhong area, Tarim Basin, western China. Marine and Petroleum Geology. 2013. 43: 88-101
- Pang X Q, Tian J, Pang H, et al. Main progress and problems in research on Ordovician hydrocarbon accumulation in the Tarim Basin. Petroleum Science. 2010. 7(2): 147-163
- Qian Y X, He Z L, Chen Q L, et al. Sealing capacity of the Ordovician carbonate rocks in Tazhong area, the Tarim Basin. Oil & Gas Geology. 2012. 33(1): 1-9 (in Chinese)
- Tang L J, Huang T Z, Qiu H J, et al. Salt-related structure and deformation mechanism of the Middle-Lower Cambrian in the middle-west parts of the Central Uplift and adjacent areas of the Tarim Basin. Science in China: Earth Sciences. 2012. 55(7): 1123-1133
- Tian Y K, Zhao J, Yang C P, et al. Multiple-sourced features of marine oils in the Tarim Basin, NW China—Geochemical evidence from occluded hydrocarbons inside asphaltene. Journal of Asian Earth Sciences. 2012. 54-55(2): 174-181
- Wang F Y, Bian L Z, Zhang S C, et al. Two types of hydrocarbon generation organic matters in Ordovician marine source rocks, Tarim Basin. Science in China Series D: Earth Sciences. 2001. 31(2): 96-102 (in Chinese)
- Wang X D, Jiang Z X, Pang X Q, et al. Comprehensive evaluation of sealing ability of Silurian cap rocks in Tarim Basin. Journal of Xi'an Shiyou University (Natural Science Edition). 2004. 19(4): 49-53 (in Chinese)
- Yuan S Q, Jia C Z, Gao R S, et al. Sedimentation characteristics and reservoir geological model of Mid-Lower Ordovician carbonate rock in Tazhong northern slope. Acta Petrologica Sinica. 2012. 33(S1): 80-88 (in Chinese)
- Zhang J, Pang X Q, Liu L F, et al. Distribution characteristics and petroleum geological significance of the Silurian asphaltic sandstones in Tarim Basin. Science in China Series D: Earth Sciences. 2004. 47(S2): 199-208
- Zhang N, Tian L, Xing Y L, et al. Characteristics of hydrocarbon fluid inclusions and analysis of reservoir formation in Ordovician reservoirs of Tazhong area, Tarim Basin. Acta Petrologica Sinica. 2011a. 27(5): 1548-1556 (in Chinese)
- Zhang S C, Gao Z Y, Li J J, et al. Identification and distribution of marine hydrocarbon source rocks in the Ordovician and Cambrian of the Tarim Basin. Petroleum Exploration and Development. 2012. 39(3): 305-314
- Zhang S C, Hanson A D, Moldowan J M, et al. Paleozoic oil-source rock correlations in the Tarim Basin, NW China. Organic Geochemistry. 2000. 31(4): 273-286
- Zhang S C, Zhang B M, Li B L, et al. History of hydrocarbon accumulations spanning important tectonic phases in marine sedimentary basins of China: Taking the Tarim Basin as an example. Petroleum Exploration and Development. 2011b. 38(1): 1-15
- Zhang Y Y, Zwingmann H, Liu K Y, et al. Hydrocarbon charge history of the Silurian bituminous sandstone reservoirs in the Tazhong Uplift, Tarim Basin, China. AAPG Bulletin. 2011c. 95(3): 395-412
- Zhu X M, Gu J Y, Jia J H, et al. Assessment of Reservoir and Cap Rock of the Key Strata Series in the Tarim Basin. Beijing: Petroleum Industry Press. 2003: 264-300 (in Chinese)

(Edited by Hao Jie)