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THE CHARACTERISTICS AND MAIN CONTROL FACTORS OF HYDROCARBON ACCUMULATION OF ULTRA-DEEP MARINE CARBONATES IN THE TARIM BASIN, NW CHINA-- A REVIEW

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Abstract: The Lower Palaeozoic deep marine strata of the Tarim Basin are rich in petroleum resources and show bright prospect of exploration. The Tarim Basin is a typical multicycle superimposed cratonic basin. The Tarim Basin experienced a number of significant structural changes, resulting in a complex reservoiring process of oil and gas with the characteristics of "multi-source hydrocarbon supply, multi-stage reservoir, and mixed adjustment". The Cambrian-Ordovician hydrocarbon source rock in the Tarim Basin can be divided into three sets of source rocks: the Mid-Lower Cambrian, Mid-Lower Ordovician, and Upper Ordovician ones. The low geothermal gradient in the Tarim Basin contributed to the late oil generation of Cambrian and Ordovician oil-gas source rocks. The oil and gas of ultra-deep marine carbonates in the Tarim Basin generally commonly originated from multiple source rocks. The ultra-deep carbonate reservoirs in the Tarim Basin include four types, namely, reef-bank reservoir, dolomite reservoir, karst reservoir, and fracture reservoir, which are jointly controlled by factors of structure, strata sequence, facies, and fluid. The ultra-deep carbonate reservoirs in the Tarim Basin experienced multiple oil and gas accumulation period. The first accumulation period occurred in the late Caledonian period, the second one in the late Hercynian period, and the third one in the Himalayan period. The petroleum reservoir in the Tarim Basin is characterized by obvious multi-stage sealing and layered enrichment. Many types of pathways of migration were developed in the Tarim Basin, such as unconformities, faults, fractures, permeable transport layers, and volcanic piercement. The validity of pathways of hydrocarbons migration mainly depends on the location of source rocks and the matching relation between the period of hydrocarbon generation and migration and the formation of pathways. The formation and distribution of petroleum reservoir in the Tarim Basin is mainly controlled by factors of palaeouplift, palaeoslope, hydrocarbon source, regional seal, and structural balance zone.

Keywords: Main control factors, Hydrocarbon accumulation, Ultra-deep marine carbonates, Tarim Basin

1. INTRODUCTION

The Tarim Basin is rich in oil and gas resources, with the natural gas reserve of $(8.5\sim10)\times10^{12}m^3$ and the total petroleum reserve up to 200×10^8 t (Kang, 2001). According to the last decade of exploration in the Tarim Basin, the depth of oil and gas fields were mainly deeper than 4000 m, which indicated the abundant oil and gas resources and bright prospect of exploration in the deep and ultra-deep layers of the Tarim Basin, China (Zheng et al., 2004; Chen et al., 2000).

The "ultra-deep layer" refers to the exploration area with the depth of target layer over 6000 m (where the depth of target layer for the "deep layer" is about 4500-6000 m) (He et al., 2016). The Tahe Oilfield in the Tarim Basin is the deep and ultra-deep marine carbonate oilfield with the largest proved reserves in China (Zhao et al., 2015). Its hydrocarbon source rock is Cambrian-Ordovician one and the main target layers of exploration are Ordovician Yingshan Formation, Yijianfang Formation, and Lianglitage Formation, with a main reservoir type of karst fracture-cave and an average well depth over 6000 m. Recently, the north and southwest of the Tahe Oilfield were developed as bright prospect areas to increase reserves (He et al., 2016). At present, three oil and gas accumulation zones have been found, including Shaya Uplift, Tazhong Uplift, and Bachu Uplift-Markit Slope (Fig. 1). The hydrocarbon reserves in the Lower Palaeozoic carbonate rock is up to 17×10^8

t and the oil equivalent is over 22× 10^8 t (Qi, 2014).

In Bachu Uplift, Well He-4 began to reveal that the thickness of the Middle Cambrian salt layer is 385 meters. Well Fang-1 drilled through a 350m-thick salt layer and in Tazhong Uplift, Well Tacan-1 revealed that the gypsum layer is 40m thick. Subsequent Wells Kang-2, Hetian-1, Tong-1, He-6, Batan-5 and Mabei-1 in Bachu uplift were drilled and those six wells proved that there are two sets of reservoir and cover combinations in the Middle and Lower Cambrian (Wang et al., 2014). Well Tashen-1 (having the bottom to the 8408 m, temperature over 170℃, and pressure over 80 MPa, the deepest well in Asia for the moment), revealed ultra-deep high-quality reservoirs in the Cambrian strata of the Shaya Uplift.

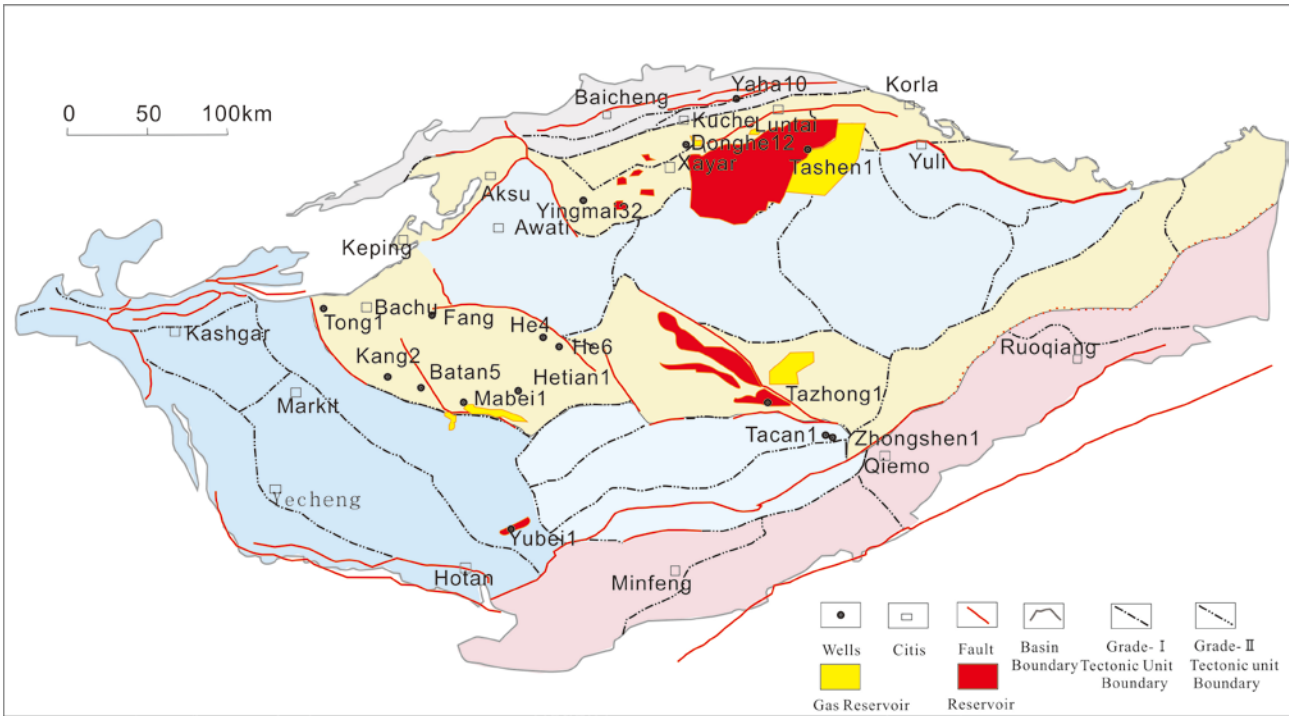

Figure 1. Present situation of carbonate exploration in the Lower Paleozoic petroleum system in the Tarim Basin (Qi, 2014; Wang et al., 2014; You et al., 2014; Shen et al., 2016, Ma et al., 2015)

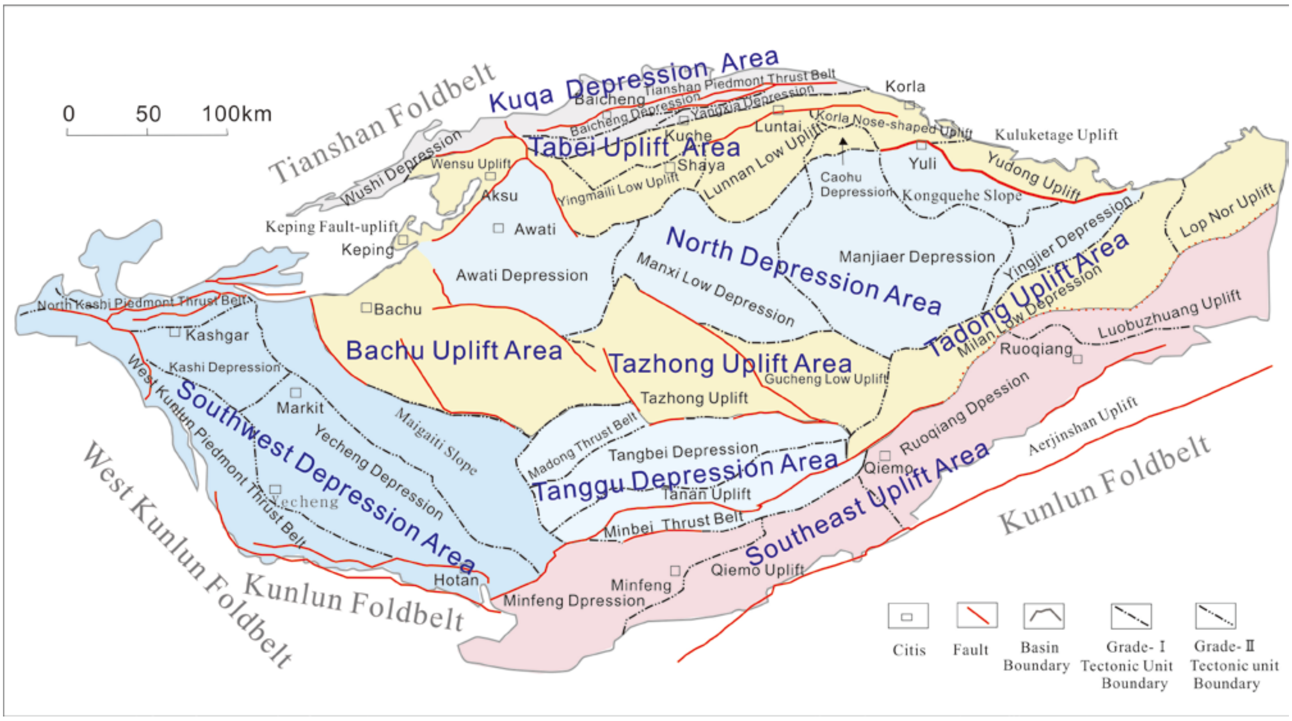

Figure 2. Tectonic setting of the Tarim Basin, north-western China (Ma et al., 2015)

Recently, the ultra-deep Well Zhongshen-1 was a breakthrough and discovered the original oil and gas reservoir in Cambrian subsalt dolomite, which is of great significance to oil and gas exploration of Tarim Basin (Wang et al., 2014).

In a word, all those drilled wells in Bachu and Tazhong Uplifts indicated the abundant oil and gas resources and bright prospect of exploration in the Lower Palaeozoic ultra-deep marine carbonate of the Tarim Basin (He et al., 2016).

2. STRUCTURAL CHARACTERISTICS OF THE TARIM BASIN

The Tarim Basin is surrounded by the Kunlun, Tian Shan and Altyn Tagh mountains (You et al., 2013; You et al., 2014). During the long-term evolution of the Tarim Basin, the internal structure of the basin reflects a complex geological history. One of the distinctive features of the Tarim Basin is the development of a series of regional tectonic unconformities and basin-scale palaeouplift belts, showing the complex geologic structure of the basin (Jia, 1997). The shape of the Tarim Basin is like a rhombus. Based on sedimentary and structural evolutions, two major tectonic classification have been used and are currently guiding petroleum exploration. In the first classification, the Tarim Basin can be divided into five first-grade structural units consisting of 20 secondary structural units shown in Table 1 (Jia, 1997, Ma et al., 2015). In the other classification, the Tarim Basin is composed of nine first-grade structural units called “five uplifts and four depressions”, and secondary structural units are further subdivided shown in Figure 2 and Table 1.

There were six evolution stages in the Tarim Basin during the Phanerozoic (Li et al.,2016): (1) an intra-cratonic extensional basin stage during the Sinian-Early Ordovician, (2) an intra-cratonic compressional basin stage during the Middle Ordovician-Middle Devonian, (3) a back-arc extensional basin stage during the Late Devonian–Early Permian, (4) a retro-arc foreland basin stage during the Late Permian–Triassic, (5) a collisional reactivated foreland basin stage during the Jurassic–Paleogene, and (6) an Indian–Tibetan collisional successor basin stage during the Neogene-Quaternary.

3. CHARACTERISTICS OF THE LOWER PALAEOZOIC STRATA IN THE TARIM BASIN

During the Cambrian period, the depositional framework of the western Tarim Basin was a platform type, while the eastern was cratonic deep-water basin. There were great differences of the rock strata between Bamai-Tazhong-Tabei area (the platform facies) and Tadong area (the basin facies).

In the platform facies (the Bamai-Tazhong-Tabei area), six formations were developed from the bottom to the top in the Cambrian system:

(1) The Lower Cambrian Series:

-Yuertusi Formation ($\in_{1y}$) is composed of sedimentary rocks deposited under massive seawater invasion environment.

-Xiaoerbulake Formation ($\in_{1x}$, the dolomite strata under gypsum sections) is mainly composed of gray and dark-gray dolomite and algal dolomite with horizontal beddings formed under restricted platform.

-Wusonggeer Formation ($\in_{1w}$, the lower gypsum section) is mainly composed of brown, purplish red and gray gypsum, deposited under evaporation environment.

(2) the Middle Cambrian Series:

-Shayilike Formation ($\in_{2s}$, the limestone section between gypsum sections) is mainly composed of carbonate rock, which is divided into dolomite section of the lower part and micritic limestone section of the upper part.

-Awatage Formation($\in_{2a}$, the upper gypsum section) is mainly composed of brown and gray gypsum, gypsum dolomite, and pupple argillaceous dolomite, which were deposited in evaporation platform environment.

(3) the Upper Cambrian Series: Xiaqiulitage Formation ($\in_{3xq}$, the dolomite strata over gypsum sections) is a thick layer of restricted platform deposition as a whole, where its lithologic character shows obvious overlapping sequence of dolomite.

In the basin facies (the Tadong area), the Cambrian system consists of four strata from bottom to top:

(1) the Lower Cambrian Series: Xishanbulake Formation ($\in_{1x}$) is mainly composed of black siliceous mudstone, with black siliceous fine dolomite and dark gray fine sandstone at the bottom.

(2) the Middle Cambrian Series:

-Xidashan Formation ($\in_{1xd}$) has black mudstone with black lime dolomite and fine limestone in the lower part and black micrite lime dolomite with mudstone and siliceous rock in the upper part in the Kongquehe area.

-Moheershan Formation ($\in_{2m}$) has gray limestone, mud limestone, and mudstone in the upper part and light gray limestone with purplish red limestone in the lower part in the Kongquehe area.

Table 1. Division of tectonic units in Tarim Basin (after Ma et al., 2015 and Jia, 1997)

Nine first-grade structural units		Five first-grade structural units					
First-grade structural units	Secondary structural units	First-grade structural units	Area km^2	Secondary structural units	Area km^2	Third-grade structural units	Area km^2
Kuche Depression	Wushen Depression Baicheng Depression Yangxia Depression Tianshan Piedmont Thrust Belt	Northeast Depression area	>177100	Kuche Depression	31200	Wushen Depression	8800
						Baicheng Depression	15100
						Yangxia Depression	7300
						Shaxi Uplift	9600
Tabei Uplift	Wensu Uplift Yingmaili Low Uplift Luntai Uplift Lunnan Low Uplift Caohu Depression Kuerle Nose Salient Yudong Uplift			Shaya Uplift	31600	Hahatang Depression	3900
						Yakela Fault Block	4400
						Akekule Uplift	6600
						Caohu Depression	4200
						Kuerle Nose Salient	2900
North Depression	Awati Fault Depression Manxi Low Depression Manjiaer Depression Yingjisu Depression Kongquehe Slope			Awati Fault Depression	30200		
				Shuntuoguole Low-uplift	28800		
				Manjiaer Depression	49900		
				Kongquehe Slope	>25300		
		Central Uplift Zone	>120200	Bachu Uplift	47500		
Bachu Uplift				Katake Uplift	24500		
Tazhong Uplift Area	Tazhong Uplift Gucheng Low Depression			Tanggubasi Depression	15600		
				Guchengxu Uplift	32600		
		Southwest Depression Area	>120100	Maigaiti Slope	53600		
Tadong Uplift	Milan Low Uplift Lop Nor Uplift			Kashi Depression	>21700		
Tanggu Uplift	Madong Thrust Belt Tangbei Depression Tangnan Uplift			Shacheng Uplift	7300		
				Yecheng Depression	37500		
		Southeast Fault-uplift Area	>107000	Beiminfeng-Luobuzhuang Fault Uplift	>32200	North Minfeng Fault Convex	14100
Southwest Depression	Maigaiti Slope Kashi Depression Yecheng Depression North Kashi Piedmont Thrust Belt West Kunlun Piedmont Thrust Belt					Luobuzhuang Fault Convex	>18100
				Yutian-ruoqiang Depression	>74800	Yutian Depression	26900
						Aqiang Uprift	13200
						Ruoqiang Depression	34700
Southeast Uplift	North minfeng Thrust Belt Luobuzhuang Uplift Minfeng Depression Qiemo Uplift Ruoqiang Depression	Marginal Uplift Area	>289700	Keping Uplift	19400		
				Tiekelike Uplift	18300		
				Kuluketage Uplift	222000		
				Aerjinshan Uplift	30000		

(3) the Upper Cambrian Series: Tuershaketage Group ($\in_{3te}$) has gray black limestone, nodular limestone, and calcareous shale in Kongquehe area. In Tadong area, this group develops gray black micrite limestone with some dolomite in the lower part and gray black nodular micrite limestone and calcareous mudstone in the upper part.

During the Ordovician period, the depositional framework of the western Tarim Basin was also a platform type, while the eastern was cratonic deep-water basin. In the west of the basin, carbonate platform facies were the main sedimentary facies. The litho-stratigraphic sequence can be divided into Penglaiba Formation, Yingshan Formation, Yijianfang Formation, Qiaerbake Formation, Lianglitage Formation, and Sangtamu Formation from bottom to top. In the east of the basin, basin and slope facies were the main sedimentary facies and clastic rocks were dominant. The litho-stratigraphic sequence can be divided into Upper Tuershaketage Group, Heituao Formation, Queerqueke Formation from bottom to top (Fig. 3; Lü et al., 2014).

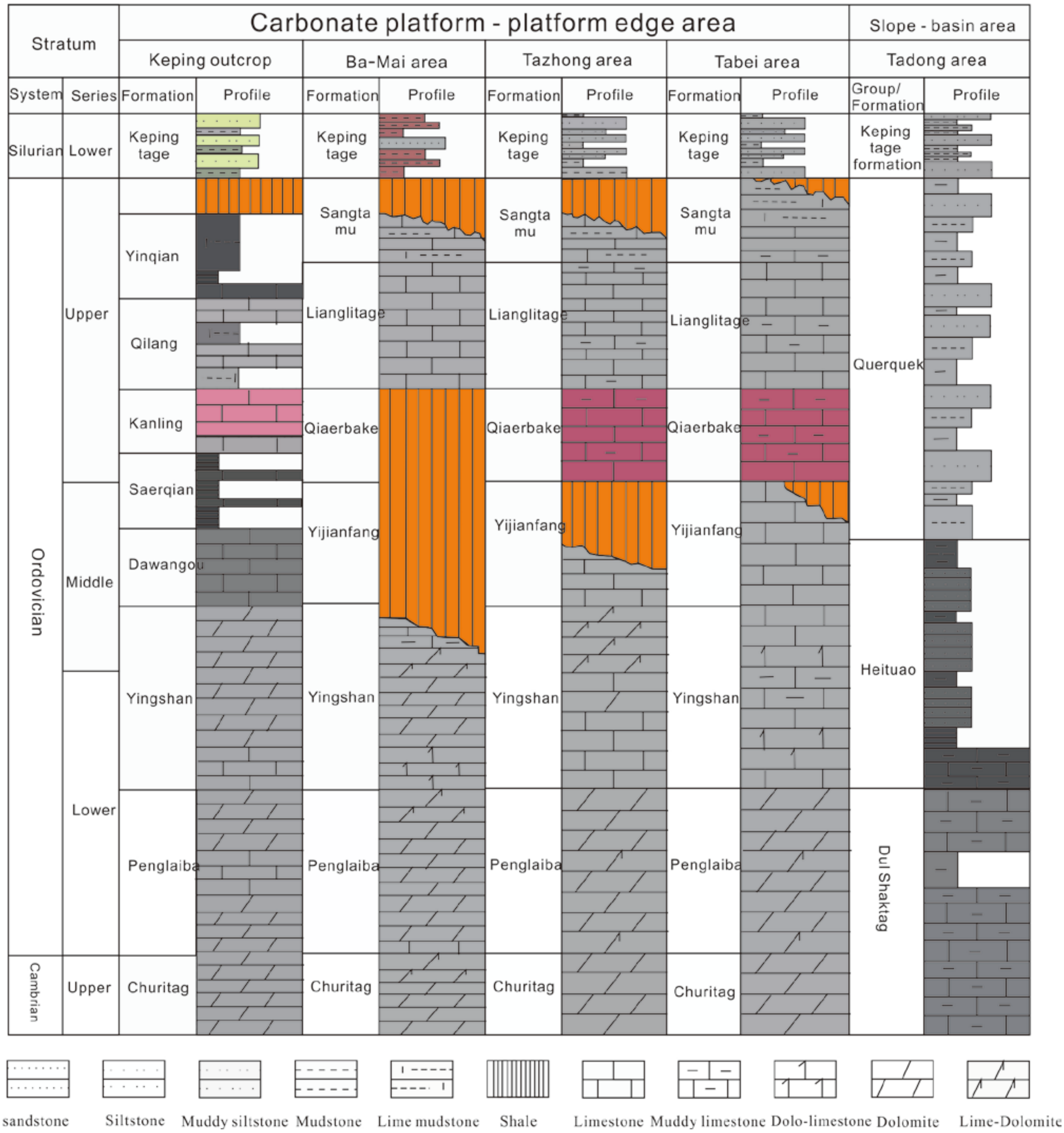

Figure 3. Correlation of the Ordovician in Tarim Basin (Lü et al., 2014)

4. CHARACTERISTICS AND MAIN CONTROL FACTORS OF HYDROCARBON ACCUMULATION OF ULTRA-DEEP MARINE CARBONATES IN THE TARIM BASIN

4.1 Distribution of hydrocarbon source rock and origins of petroleum

After multicycle structural evolutions, the Tarim superimposed basin has multiple sets of hydrocarbon source rocks, reservoirs, and seals, and multi-stage hydrocarbon generations and accumulations. The Tarim Basin mainly has three sets of hydrocarbon source rocks, namely, Cambrian-Ordovician, Carboniferous-Lower Permian, and Triassic-Jurassic (Zheng et al., 2004). The Cambrian-Ordovician hydrocarbon source rock can be further divided into three sets: Mid-Lower Cambrian series, mid-lower Ordovician series, and Upper Ordovician series (Wang et al., 2014).

The hydrocarbon source rock in the eastern Tarim basin is mainly the upper part of Lower Cambrian Xishanbulake Formation ($\in_{1x}$), Xidashan Formation ($\in_{1xd}$), lower part of Middle-Cambrian Moheershan Formation ($\in_{2m}$), and Mid-Lower Ordovician Heituao Formation ($O_{1+2\ ht}$). The hydrocarbon source rock in the western Tarim basin is mainly Lower Cambrian Yuertusi Formation ($\in_{1y}$), mid-upper Ordovician Saergan Formation (Lv et al., 2014). Being affected by the structural evolution, there are three major hydrocarbon source rocks areas, including the west margin of Manjiaer Depression, Awati Depression, and the south area of Taxinan Depression. Because the heterogeneity of carbonate strata makes long-distance migration of oil and gas difficult, the oil and gas is mainly distributed in the areas around three major hydrocarbon source rocks areas (He et al., 2016). There is low geothermal gradient in the Tarim Basin, with the geothermal gradient less than 2° C/100 m at present (Ye et al., 1991). The low geothermal gradient contributed to the late oil generation of Cambrian and Ordovician oil-gas source rocks.

The fluids in reservoirs of the Tarim superimposed basin show multi-phase distribution. For example, the fluids in the Ordovician reservoirs have diverse types, such as the normal black oil, condensate oil, weak volatile oil, heavy oil, asphalt, and natural gas. The natural gas can be divided into dry gas and wet gas. Even in a single reservoir, several phases of oil and gas co-exist, indicating the extremely complex properties of the fluids (Pang et al., 2012).

Until now, there have been many researches on the origins of Palaeozoic crude oil in the Tarim Basin. It is regarded that the oil and gas in Tahe Oilfield is mixed crude oil with different maturity degrees and sedimentary environments. Petroleum from the Ordovician reservoir in Tahe Oilfield originated from high-quality Cambrian to Lower Ordovician ($\in_1$-O_1) hydrocarbon source rocks and Mid-Upper Ordovician (O_3-O_2) carbonate hydrocarbon source rocks. The crude oil in Yubei area is mixed oil generated by at least, two petroleum injection. The early-filling oil was strongly degraded and mainly originated from the middle-Upper Ordovician source rocks (Zhang et al., 2007).

However, there are significant differences between the source rock samples obtained from outcrops and the discovered oil and gas and lack of systematic comparative studies on the samples of hydrocarbon source rocks. There is still great controversy on recognition of the oil source. At present, the main controversy focuses on whether the main oil source was Cambrian series or Ordovician series (Zhao et al., 2008; Gu, 2000; Li et al., 2000; Sun et al., 2004).

For natural gas, there is both sapropelic and humic gas in the Tarim Basin. The humic gas in Tarim Basin, mainly distributed in the margin area of the Tarim Basin, primarily originated from the Triassic-Jurassic coal series. The marine sapropelic gas results mostly from Cambrian-Ordovician marine facies hydrocarbon source rocks (Liu et al., 2009). The marine sapropelic gas is essentially distributed in the Northeast Depression, the Central Uplift, and the north of Southwest Depression. The apropelic gas in the Tarim Basin can be further divided into kerogen cracking gas and oil cracking gas (Liu et al., 2009).

4.2 Types and Characteristics of Reservoirs

The ultra-deep carbonate reservoirs of the Tarim Basin are comprised of four types: reef-bank, dolomite, karst, and fracture reservoirs (He et al., 2016).

The reef-bank facies are a kind of carbonate reservoir controlled by sedimentation and paleogeographic environment. The lithology is mainly bioclastic limestone and grain limestone. The reservoir spaces include organic lattice pores, visceral pores, intergranular pores, and intergranular dissolved pores. For instance, the Yijianfang Formation and Yingshan Formation in Tabei area develop the reef-bank facies reservoirs.

The dolomite reservoirs include the evaporitic tidal flats (sabkhas) dolomite reservoir, buried dolomite reservoir, and tectonic-hydrothermal dolomite reservoir. The lithology of the evaporitic tidal flats (sabkhas) dolomite is mainly composed of micrite dolomite, and the reservoir spaces are dominated by dissolution pores of gypsum concretion, intergranular pores, and a small amount of intercrystal pores, such as the Lower-Middle Cambrian Well Hetian-4, Well Yaha-10 in Tabei, Tazhong areas. The lithology of buried dolomite reservoir is mainly composed of fine, medium and coarse crystalline dolomites, and reservoir spaces are dominated by intercrystal pores, intercrystal dissolved pores, and a small amount of dissolved pores and vugs, such as the Upper Cambrian in Tabei, Tazhong, and the Lower Ordovician Penglaiba Formation (Well Donghe-12, Well Yingmai-32 and so on). The tectonic-hydrothermal dolomite is represented by saddle dolomite, which is patchy and controlled by the fault, and the reservoir spaces are mainly composed of residual cavities and intercrystal pores (Shen et al., 2016; Liu et al., 2016).

The atmospheric water leaching can dissolve the exposed carbonate rocks into complex seam-cave reservoir systems (mostly developed in limestone strata) and vug reservoir systems (mostly developed in dolomite strata). They are further divided into 3 categories by Zhao et al. (2012): limestone buried hill (weathering crust) karst, interstratal karst, and bedding karst, which are all controlled by atmospheric water dissolution and composed by different sizes of cave - seam systems.

The dissolution by magmatic hydrothermal fluids and by organic acids which are included in the multiphasic hydrocarbons and multiphasic accumulations are also an important controlling factor for reservoir properties (Zheng et al., 2007). In addition, gypsum is generally developed in the Middle Cambrian in the Tarim Basin. Thermochemical sulfate reduction (TSR) between gypsum salt and hydrocarbons might occur under high temperature thermodynamic conditions, which produces H_2S and CO_2 and other acidic gases, resulting in high-quality reservoir by strong dissolution.

A series of normal faults developed from the Sinian to Early Cambrian in the Tarim Basin were converted into high-angle abnormal faults with fractures in the Ordovician, which can act as storage spaces and migration pathways for fluids. In addition, because dolomite is more brittle than limestone, it is more likely to break and produce cracks than limestone as the burial depth increases, which is favorable for keeping reservoir properties (Zheng et al., 2007).

The development of ultra-deep carbonate reservoirs is the result of the combined controls of structure, sequence, lithofacies, and fluids. Among them, faulting, dolomitization, and hydrothermal fluid activity are particularly critical for the formation of ultra-deep high-quality reservoirs (He et al., 2016).

4.3 Seal condition

Because the Tarim Basin experienced long and complicated tectonic evolutions and reconstruction, the strata were deformed intensely and fractures were growing. The hydrocarbon accumulation in the Tarim Basin has the following basic characteristics: early oil and gas accumulation, late oil and gas conversion, and final adjustment and positioning. Therefore, the existence of effective preservation conditions is the key to develop the ultra-deep reservoir (Jin, 2014).

The hydrocarbon reservoirs in the Tarim Basin show the characteristics of multi-stage capping and layering enrichment, (Fig. 4; He et al., 2016). There are four sets of regional cap rocks developed in the Lower Paleozoic in the Tarim Basin, (Fig. 4). They are the Middle Cambrian gypsum mudstone, the Upper Ordovician Sangtamu Formation, the Silurian (mudstone section), and the Carboniferous gypsum mudstone. The Middle Cambrian gypsum mudstone is mainly distributed in the Bachu uplift, the Maigaiti slope, the Tazhong uplift and the Awati depression, forming a favorable reservoir-cap assemblage with the Cambrian under-salt and inter-salt dolomite reservoirs. The Upper Ordovician Sangtamu Formation distributes in the Tazhong uplift and the Tabei uplift, forming a favorable reservoir-cap assemblage with the reservoir of the Ordovician karst weathering crust reservoirs and the reef and bank facies reservoirs. The Silurian cap rock is mainly composed of reservoir-cap assemblages with the Silurian reservoir, which is mainly distributed in Bachu uplift, west of Maigaiti slope, and Tabei uplift. The Carboniferous gypsum mudstones are widely distributed, but they are mainly forming the effective reservoir-cap assemblage in the uplift area with Ordovician weathered crust reservoirs (Fig. 4, He et al., 2016).

The oil and gas accumulation in Tabei and Tazhong is controlled by a set of regional cap rocks of the Upper Ordovician Sangtamu Formation. In addition, there are several sets of tight barrier beds in the Lower Ordovician Yingshan Formation, which are mainly composed of micrite limestone. The seals were unstable in the horizontal direction, and overlaying each other in the vertical direction. They form a good relationship with the underlying oil and gas layers. One or more sets of reservoir-cap assemblages are formed, controlling the accumulation of oil and gas layers (He et al., 2016).

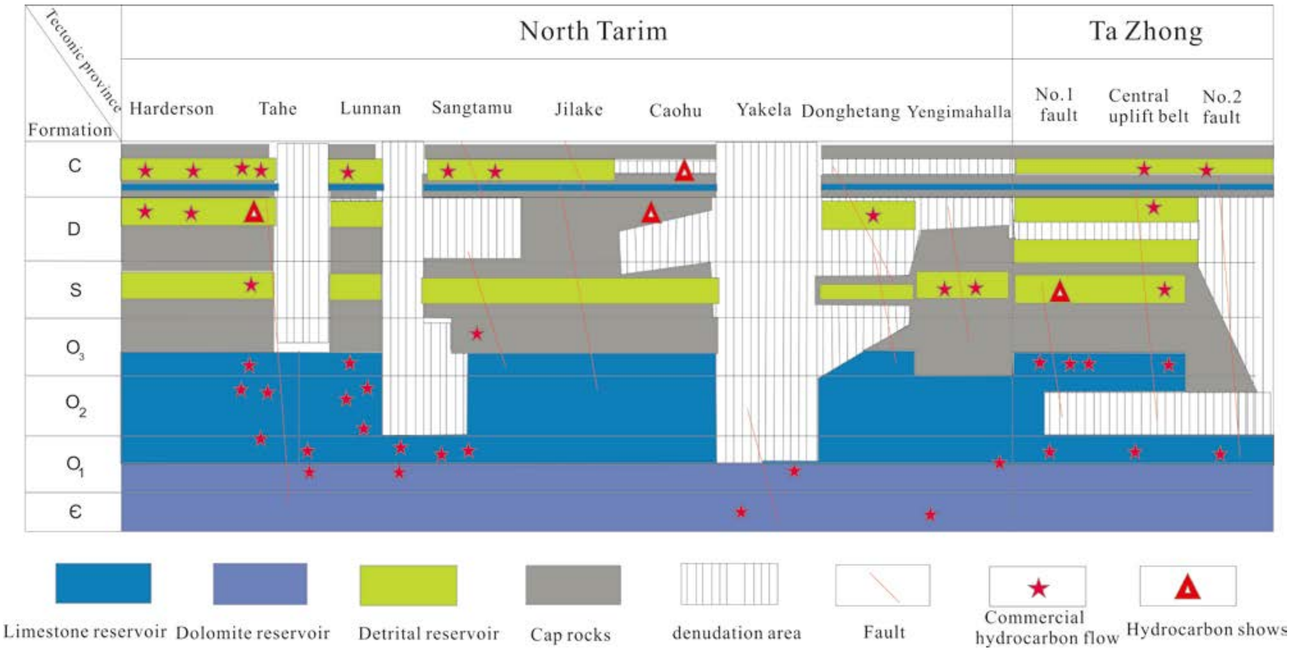

Figure 4. Vertical distribution of reservoir and cap rock in Tarim Basin (He et al., 2016)

A breakthrough is found in the Lower Cambrian dolomite reservoirs below gypsum in the Tarim Basin by Well Zhongshen-1, which brings a new chapter in the exploration of the Cambrian dolomite. It indicates that the Middle Cambrian evaporative rock is also an effective seal, which plays the role of a strong cap and efficiently protected ancient reservoirs (Wang et al., 2014).

The marine facies in the Tarim basin has old age and has undergone several strong tectonic movement. The preservation conditions after petroleum accumulation are most critical. Therefore, it is the key element to further understand the preservation process and mechanism of hydrocarbon accumulation of the marine carbonate in the Tarim Basin. For example, through counting the Ordovician high-yield wells in Tazhong and the thickness of mudsonte in the Sangtamu Formation, it is found that the mudstone thickness is basically more than 200 m. There is positive correlation between the oil and gas production and the thickness of mudstone cap rock as “the greater the cap thickness, the greater the oil and gas production” (He et al., 2016).

4.4 The types and effectiveness of the pathways of the hydrocarbons migration

The broad plane distribution and vertical multi-layer system of oil and gas are closely related to the type and spatial distribution of oil and gas transport systems. There are various types of oil and gas transport systems in the Tarim Basin, such as unconformity, faults, fractures, permeable transport beds. Faults were efficient channels for vertical migration of oil and gas, controlling here their vertical distribution. Unconformities are long-distance channels for lateral migration, which control the plane distribution of petroleum. Permeable transport beds play similar roles in migration channels and accumulating spaces. The existance of fractures can increase permeability and reduces the oil and gas migration resistance, improving the reservoir properties significantly (Wu et al., 2009).

Although there are various types of transport systems in the Tarim Basin, not all of them are effective. Their effectiveness depends on many factors, such as the source rocks position, generation and expulsion periods, combination of migration and transport systems effective periods, assembled spatial orientation of transmission conductors, and locations of paleouplift and paleotectonic ridge (Wu et al., 2009).

The effective transport through unconformities and faults in ultra-deep carbonate reservoirs is one of the main elements controlling hydrocarbon accumulation and enrichment (Wang et al., 2012). The structural location, surrounding fracture characteristics, reservoir development, testing deliverability, and testing results show that the discovery rates of oil and gas are high in the exploration wells with synchronous development of reservoir and fracture in the Tazhong area.

4.5 The filling history of the Tarim Basin oil and gas system

The Lower Paleozoic carbonate strata in the Tarim Basin experienced several significant structural changes, resulting in a complex reservoiring process of oil and gas, with the characteristics of “multi-source hydrocarbon supply, multi-stage reservoir, and mixed adjustment”. The predecessors have made a systematic summary and analysis on the geological conditions, main controlling factors, hydrocarbon’s source, filling history, and oil-gas accumulation mechanism of the Lower Paleozoic oil-gas fields in the Tarim Basin.

Chen et al (2014) studied hydrocarbon accumulation sequences of the Ordovician oil and gas fields in the Tahe, Tazhong, and areas of Bachu-Maigaiti, indicating that different tectonic evolution happened in the Lower Paleozoic in the three areas. The results show that the Ordovician karst reservoirs from all three tectonic belts have occurred of "four-episode and three-stage" oil filling and one-stage gas filling, but there are significant differences in the hydrocarbon accumulation period, sequence, and duration time (Fig. 5; Chen et al., 2014).

The first stage of hydrocarbon accumulation occurred in the late Caledonian. The second stage occurred in the late Hercynian and the Indosinian-Yanshan epoch, and represented the adjustment period of hydrocarbon (Fig. 5). The third hydrocarbon accumulation occurred in the Himalayan period. The first stage of oil and gas reservoirs formation experienced two stages of uplifting in early Hercynian and late Hercynian. The second stage experienced the uplift in late Hercynian. The reservoirs formed in the first and second periods were all residual hydrocarbon reservoir. They were possible to experience the third stage of high mature oil re-filling and gas invasion reformation (Chen et al., 2014; He et al., 2016).

5. ACCUMULATION AND DISTRIBUTION OF HYDROCARBONS

The Tarim Basin is a typical multicycle superimposed craton basin. It has undergone many important tectonic processes and superimposed evolution history, resulting in a complex hydrocarbon accumulation process with the characteristics of "multi-source rocks for hydrocarbon generation, multi-stage accumulation, and mixing adjustment" (Jin et al., 2004; Pang et al., 2012). The hydrocarbon accumulation of the Lower Paleozoic marine carbonate reservoir sets in the Tarim basin have the following features: (1) low-geotemperature background and multiple hydrocarbon generation; (2) multi-stage accumulation; (3) multi-stage capping and preservation; (4) near-source enrichment.

Kang et al., (2001) pointed out that hydrocarbon distribution in the deep strata of the Tarim Basin is mainly controlled by the ancient craton basins and the Mesozoic and Cenozoic foreland basins.

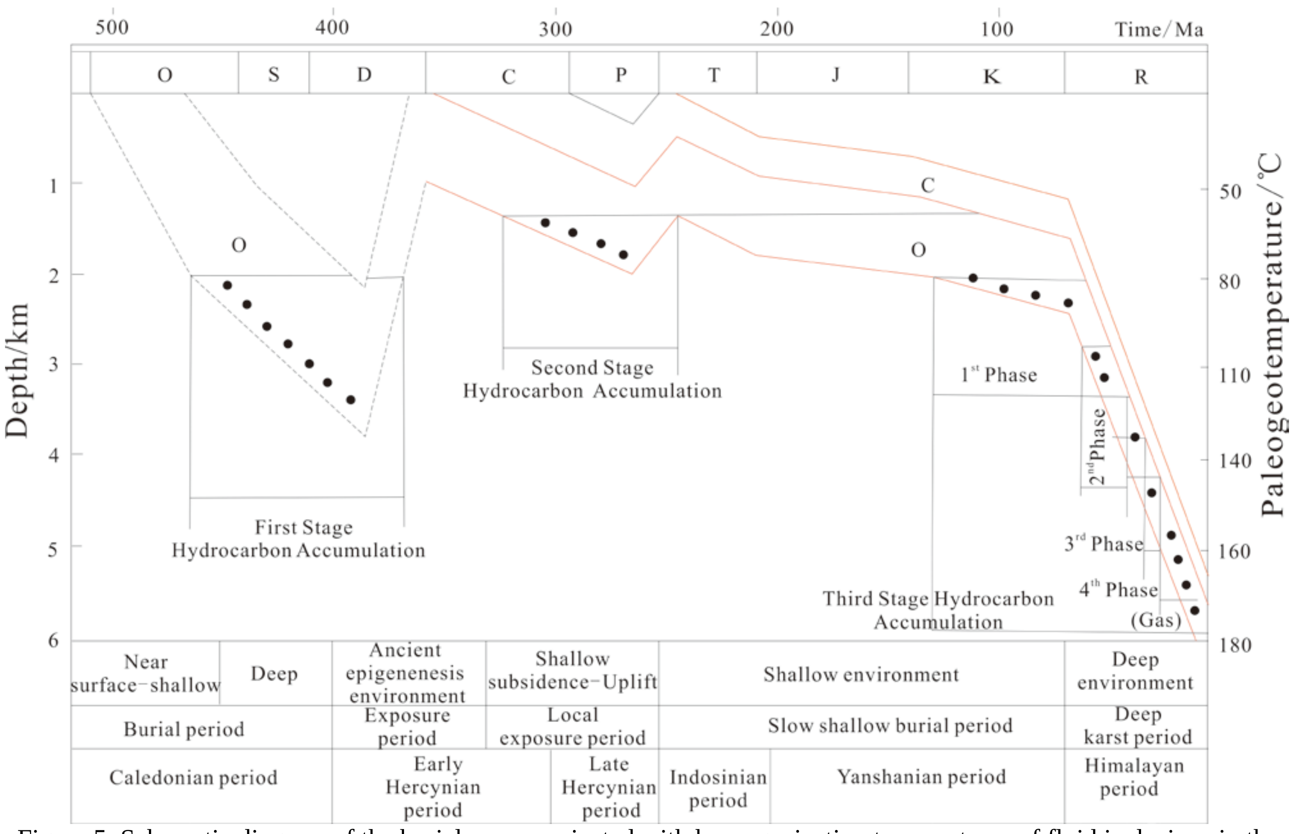

Figure 5. Schematic diagram of the burial curve projected with homogenization temperatures of fluid inclusions in the Ordovician of Tahe Oilfield (Chen et al, 2014).

For the ancient craton basins, oil and gas distributions are mainly associated with palaeouplift, paleoslope, fault zone, and regional unconformity. Oil and gas in palaeouplift and paleoslope are further controlled by secondary uplift and twisted structure zone. Pang et al. (2008) pointed out that the formation and distribution of oil and gas reservoirs are mainly controlled by the four elements: palaeouplift, hydrocarbon source rocks, regional cap rock, and tectonic equilibrium zone. Jin (2012) put forward a new idea of "source and cap controlling hydrocarbon and junction of slope controlling accumulation". He points that slope and structural hinge zones are favorable areas for hydrocarbon accumulation. The marine carbonate depositional slope is the favorable area for the development of high-quality source rocks, reservoirs and cap rocks. The structural hinge zones are the other favorable areas for the development of modified high-quality marine carbonate reservoirs, the focus areas for hydrocarbon migration and the favorable place for hydrocarbon preservation (Jin et al., 2009, Jin, 2012).

According to the evaluation idea of "source and cap controlling hydrocarbon and junction of slope controlling accumulation", the area surrounding the Manjiaer depression, especially the transitional zone of Awati depression and Manjiaer depression, developed best Cambrian and Lower Ordovician source rocks, and is the most favorable exploration area in the deep layers. Combined with the distribution of ultra-deep marine reservoirs in the Lower-Middle Cambrian, the shallow buried Tabei uplift and the central uplift belt are thought as a favorable prospecting area in the near future (He et al., 2016).

6. CONCLUSION

1) There are abundant oil and gas resources in the Lower Paleozoic ultra-deep marine strata in the Tarim Basin, which is a typical multicyclical superimposed craton basin of Tarim. The Tarim Basin has undergone many important tectonic processes and superimposed evolution history, resulting in a complex hydrocarbon accumulation process of "multi-source hydrocarbon supply, multi-stage reservoir, and mixed adjustment".

2) The Cambrian - Ordovician source rocks from the Tarim Basin belong to the following stratigraphic ages: the Mid-Lower Cambrian, Mid-Lower Ordovician, and Upper Ordovician ones. Tarim Basin has a lower geothermal gradient, which is favorable for the late petroleum generation of Cambrian and Ordovician source rocks, and the oil and gas commonly has mixed origins. The ultra-deep carbonate reservoirs in the Tarim Basin can be divided into four types: reef and bank facies, dolomite, karst, and fractures, which are controlled by many factors comprehensively, such as tectonic movements, stratigraphic sequence, lithofacies and fluid. The oil and gas reservoirs in Tarim Basin show obvious multi-stage capping and layering enrichment.

3) The ultra-deep carbonate reservoirs in the Tarim Basin experienced multiple oil and gas accumulation periods. The first accumulation period occurred in the late Caledonian period, the second one in the late Hercynian period, and the third one in the Himalayan period.

4) There are various types of oil and gas pathways in the Tarim Basin, such as unconformities, faults, fractures, and permeable transport beds. The effectiveness of the transport system depends on the position of the hydrocarbon source rocks, the hydrocarbon generation and expulsion period, the matching relationship between the migration period of oil and gas and the effective period of transport systems.

5) The formation and distribution of oil and gas reservoirs are mainly controlled by the four elements: palaeouplift, hydrocarbon source rocks, regional caprock, and tectonic equilibrium zone.

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