Sedimentary Environments of Cambrian–Ordovician Source Rocks and Ultra-deep Petroleum Accumulation in the Tarim Basin

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Abstract: The Tarim Basin is the only petroliferous basin enriched with marine oil and gas in China. It is presently also the deepest basin for petroleum exploration and development in the world. There are two main sets of marine Source Rocks (SRs) in the Tarim Basin, namely the high over-mature Cambrian–Lower Ordovician (∈–O_1) and the moderately mature Middle–Upper Ordovician (O_{2-3}). The characteristic biomarkers of SRs and oils indicate that the main origin of the marine petroleum is a mixed source of ∈–O_1 and O_{2-3} SRs. With increasing burial, the hydrocarbon contribution of the ∈–O_1 SRs gradually increases. Accompanied by the superposition of multi-stage hydrocarbon-generation of the SRs and various secondary alteration processes, the emergence and abnormal enrichment of terpenoids, thiophene and trimethylaryl isoprenoid in deep reservoirs indicate a complex genesis of various deep oils and gases. Through the analysis of the biofacies and sedimentary environments of the ∈–O_1 and O_{2-3} SRs, it is shown that the lower Paleozoic high-quality SRs in the Tarim Basin were mainly deposited in a passive continental margin and the gentle slope of the platform, deep-water shelf and slope facies, which has exhibited a good response to the local tectonic-sedimentary environment. The slope of the paleo-uplift is the mutual area for the development of carbonate reservoirs and the deposition of marine SRs, which would be favorable for the accumulation of petroleum. Due to the characteristics of low ground temperature, the latest rapid and deep burial does not cause massive oil-cracking in the paleo-uplift and slope area. Therefore, it is speculated that the marine reservoirs in the slope of the Tabei Uplift are likely to be a favorable area for deep petroleum exploration, while the oil-cracking gas would be a potential reserve around the west margin of the Manjiaer Depression. Hydrocarbons were generated from various unit SRs, mainly migrating along the lateral unconformities or reservoirs and the vertical faults. They eventually brought up three major types of exploration fields: middle and lower Cambrian salt-related assemblages, dolomite inner reservoirs and Middle and Lower Ordovician oil-bearing karst, which would become the most favorable target of marine ultra-deep exploration in the Tarim Basin.

Keywords: biomarkers, organic carbon isotopes, compound specific isotopes, marine source rock, deep reservoirs

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1 Introduction

The Tarim Basin is the only petroliferous basin in China where marine industrial petroleum has been explored and developed. After 30 years of exploration, the marine reserves have reached more than the equivalent of 4.68 billion tons of oil, with an annual production capacity equivalent to 12.8 million tons of oil (Yang et al., 2020). The Tarim Basin has been promoted as the most important production base of marine petroleum in China. Since the exploration breakthrough of Well SC-2 in the Tabei Uplift, commercial reserves have been discovered in eight strata from the Cambrian to the Cretaceous. The hydrocarbon reservoirs were mainly accumulated in the Ordovician, including dry gas, condensates, light oil, waxy oil, heavy oil and oil sand.

A large number of geochemical studies show that ∈–O_1 and O_{2-3} are the main marine source rocks (SRs) of the Tarim Craton (Liang et al., 2000; Zhang et al., 2004). According to the oil-source correlation of the specific biomarkers, such as dinosterane, 4-methyl-24 ethyl-cholestane and 24-norcholestane, it was determined that the genesis of most reservoirs in the uplift was mainly related to O_{2-3} SRs (Zhang et al., 2000, 2005; Ma et al., 2006; Li et al., 2010). Only some hydrocarbon reservoirs, such as the heavy oil reservoir in Well TD-2 (∈), condensate reservoirs in Well YN-2 (J) and normal oil reservoirs in Wells-TZ62 (S) and Th904 (O) possess geochemical characteristics similar to Cambrian SRs. Due to the light hydrocarbon fingerprints, tricyclic and tetracyclic terpanes, aromatic isoprenoids and sulfur isotopes, some researchers believe that most marine oils in the Tarim Basin more closely resemble ∈–O_1 SRs (Zhao and Huang, 1995; Sun et al., 2003; Cai et al., 2015).

With the constant expansion of exploration, newly discovered reservoirs have mainly been found in the slope

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of the paleo-uplift and 7000–8000 m deep strata, such as the condensates reservoir (6944 m) of the Xiaorbulake Formation ($\in_{1x}$) and the volati le oil (6497 m) of the Awatage Formation ($\in_{2a}$) discovered in Well ZS-1. Although the oil-source correlation of sterane biomarkers and *n*-alkane isotopes indicates that the volatile oil of Well ZS-1 more closely resembles the O_{2-3} SRs (Li et al., 2015; Song et al., 2016), the tectonic depths of the O_{2-3} SRs do not appear to support the fact that the oil derived from O_{2-3} SRs could charge the Cambrian reservoirs, which is the reason for the debate regarding the origin of the marine oil in the Tarim Basin. Cai et al. (2015) considered that the $\in$–O_1 SRs might be the main source of petroleum in the Tazhong Uplift, according to the oil-source correlation based on sulfur isotopes of thiophenes. However, many of these reservoirs have been altered by thermochemical sulfate reduction (TSR), leaving the origin and representativeness of sulfur isotopes uncertain.

A large number of geochemical studies show that $\in$–O_1 and O_{2-3} are the main marine SRs of the Tarim Craton (Liang et al., 2000; Zhang et al., 2004). The $\in$–O_1 SRs in the Tarim Basin have reached a high and post-mature stage ($R_o^E > 2.0\%$), while the O_{2-3} SRs are still in the middle-mature stage ($0.8\% > R_o^E > 1.2\%$). The differential hydrocarbon-generation of the two sets of SRs has led to multi-stage hydrocarbon charging, resulting in accumulation across several critical tectonic movements, commonly suffering from biodegradation and thermochemical cracking in the later stage. The superposition of multiple alterations, such as gas washing fractionation and physical adjustment (Zhang, 2000a; Cai et al., 2009; Li et al., 2012b), has resulted in the coexistence of various oil and gas reservoirs. It has also strongly modified the molecular and isotopic characteristics of the resulting hydrocarbons, which in turn has led to long-term disputes regarding the identification of hydrocarbon sources.

The O_{2-3} SRs are mainly revealed in Wells TZ-101, TZ-6, TZ-43, TZ-27, etc. The TOC of the O_{2-3} SRsranges from 0.23% to 2.56%, the thickness of effective SRs (TOC > 0.5%) being 22–75 m (Zhang et al., 2004). It is predicted that the O_{2-3} SRs are distributed in the slopes of the Tabei and Tazhong uplifts and that the lithology is marl and nodular limestone in the slope facies. However, the early predicted O_{2-3} SRs of the slope facies were not identified during the exploration of the slope area (Shunbei, Yuejin, Guole and Shuntuo blocks) in the Tarim Basin. On the contrary, the TOC enriched $\in$–O_1 SRs have been found in six boreholes in the western Tabei Uplift and the Manjiaer Sag in the Tadong Uplift. Well XH-1 (2007), drilled in the northwest of the Tabei Uplift, uncovered 29 m of high-quality $\in_1$ SRs with TOC from 1.0% to 9.43% (Zhu et al., 2014). Well LT-1 (2019), drilled in the eastern Tabei Uplift, revealed 26 m $\in_1$ SRs with TOC from 2.43% to 18.48% (Yang et al., 2020). Due to the high TOC content of $\in_1$ SRs, petroleum prospectors and geologists tend to prefer $\in_1$ SRs as the main marine SRs in the Tarim Basin. In particular, the accumulation of hydrocarbon originating from Cambrian SRs is more important for ultra-deep exploration in the Tarim Basin.

Nevertheless, the thickness of Cambrian SRs in the north depression is generally 20–30 m. The distribution of various Cambrian SRs has not been confirmed and whether the scale of Cambrian SRs is sufficient to supply the discovered petroleum reserves remains uncertain. In addition, whether the generation and migration of petroleum derived from the Cambrian and Ordovician SRs could match with the accumulation of deep reservoirs is another critical issue for deep marine exploration in the Tarim Basin. Therefore, systematical analysis of the geochemical characteristics of SRs and deep hydrocarbon reservoirs would be beneficial to clarifying the sedimentary environment and distribution range of the Cambrian–Ordovician SRs, so as to further and more effectively predict the favorable direction of deep hydrocarbon exploration in the Tarim Basin.

2 Deep Reservoirs Mainly Originated from the Mixing of Cambrian–Ordovician SRs

In recent years, the depth of discovered marine reservoirs in the Tarim Basin has generally exceeded 7000 m, the density of the crude oils in these deep reservoirs generally being less than 0.82 g/cm^3. The main types of hydrocarbon reservoirs are light oil, volatile oil and condensate. The deep reservoirs are mainly distributed in the Middle Ordovician Yijianfang Formation (O_2y) and the Lower Ordovician Yingshan Formation (O_1y) of the Shunbei, Yueman and Fuyuan areas on the south slope of the Tabei Uplift, as well as the Gucheng and Shuntuo blocks between the Cambrian–Ordovician platform marginal belt in the east of the Tazhong Uplift. Presently, the deepest reservoirs have been discovered in the lower Cambrian Wusongger Formation of the Tabei Uplift and the Xiaoerbulake Formation of the Tazhong Uplift (Fig. 1). The deep exploration of the Bachu Uplift and the Tadong Low Uplift in the west and east platform area has not yet achieved significant breakthroughs. Encounteringsuch complex properties and enrichment of deep reservoirs in the Tarim Basin, it is necessary to identify the main SRs and the controlling mechanisms on the spatial distribution of deep hydrocarbons.

Biomarkers are widely used to determine the genetic relationships among source rocks and crude oil, the type of hydrocarbon precursor and sedimentary environment, which has played an important role in discriminating the marine oil-source correlation in the Tarim Basin. At present, two groups of significant molecular characteristics have been identified from Cambrian–Lower Ordovician ($\in$–O_1) and Middle-Upper Ordovician SRs (O_{2-3}). The $\in$–O_1 SRs have relatively high contents of gammacerane, C_{35} homohopane, 24-isopropyl cholestane, 24-norcholestane and dinosterane (4α, 23, 24-trimethyl cholestane). In addition, C_{26} 20S, C_{26} 20R+C_{27} triaromatic steroid and triaromatic dinosterane are relatively abundant in $\in$–O_1 SRs (Zhang et al., 2002; 2004; Ma et al., 2006). These biomarkers possess clear biogenic properties. In addition, the 24-isopropyl cholestane, 24-norcholestane, C_{30} dinosterane, triaromatic steroid (TAS) and triaromatic dinosterane, respectively, indicate the biogenic contribution of diatoms and dinoflagellates (Hanson et al., 2000; Zhang and Huang, 2005; Yu et al., 2011). However, the O_{2-3} SRs basically present opposite

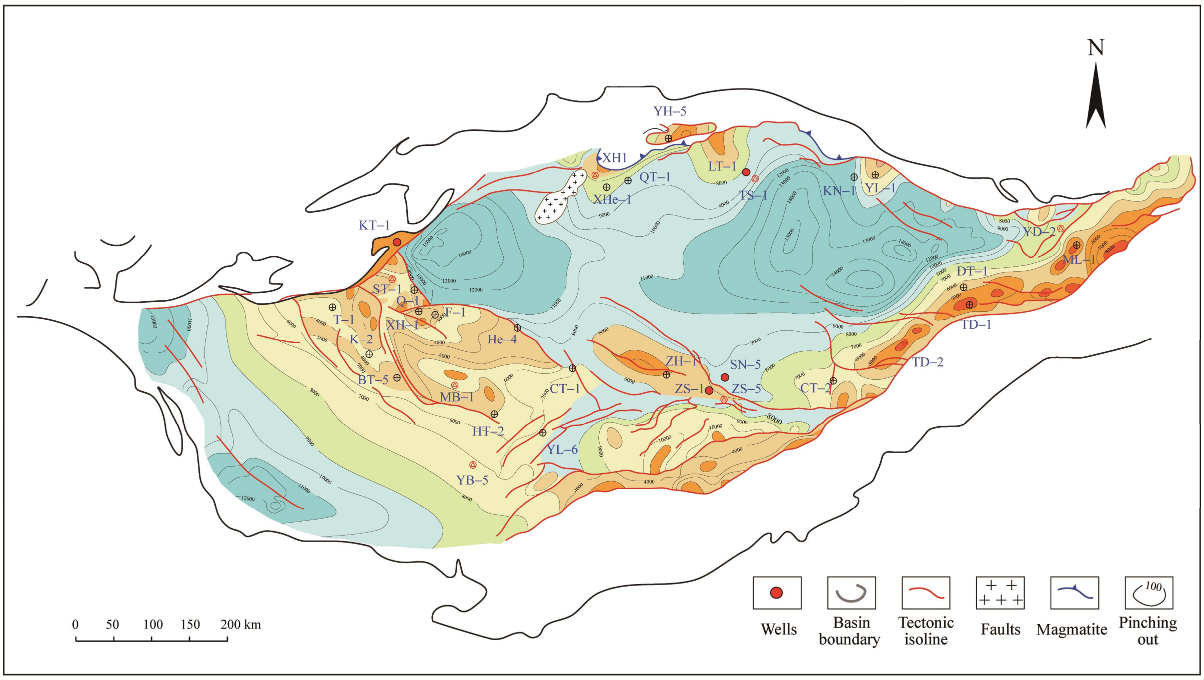

Fig. 1. The tectonic map of the Cambrian in the Tarim Basin and petroleum exploration below the depth of 7000 m.

molecular characteristics relative to ∈–O_1 SRs, regular steranes showing a 'V'-shaped distribution of C_{27}>> C_{28}<< C_{29}, with almost no aromatic dinosterane (Wang and Xiao, 2004; Li et al., 2012a).

Most of the early marine reservoirs found in the Middle-Upper Ordovician, Carboniferous and Triassic of the Tazhong and Tabei Uplifts are less than 6,500 m in depth. The biomarker composition in the marine oil more closely resembles that of O_{2-3} SRs. Only Wells TD-2, TZ-62 (S) and T-904 and the Silurian asphaltic sandstone exhibit the biomarker characteristics of ∈–O_1 SRs, indicating that O_{2-3} SRs are the main source of marine hydrocarbons, while the contribution of ∈–O_1 SRs to marine hydrocarbons in the Tarim Basin is limited (Li et al., 2015). With the continuous expansion of deep reservoir exploration from the Middle to the Lower Ordovician to the Cambrian in the marine platform, the depth of the discovered petroleum reservoirs mostly exceeds 7000 m. According to the oil source parameters of biomarkers, the deep reservoirs possess obvious mixing characteristics of Cambrian and Ordovician SRs. In addition, with the increases in maturity and the extent of oil-cracking, the contribution of Cambrian SRs to hydrocarbons has gradually risen (Fig. 2).

In contrast to the distribution of black oil and heavy oil in the reservoirs at moderate depths, the deep marine reservoirs are mainly light oil and condensate. Based on the oil-source correlation of the high-over mature oil in the deep reservoirs, most of the effective indicators of the steranes and terpanes have been cracked. In particular, the deep reservoirs have undergone multi-stage migration, accumulation and secondary alteration. Various types of crude oil, such as heavy oil, black oil, light oil, condensate, wet gas and dry gas, are sequentially formed with the increase of temperature and depth (Tissot and Welte, 1984; Horsfield et al., 1992; Hunt, 1996; Peters et

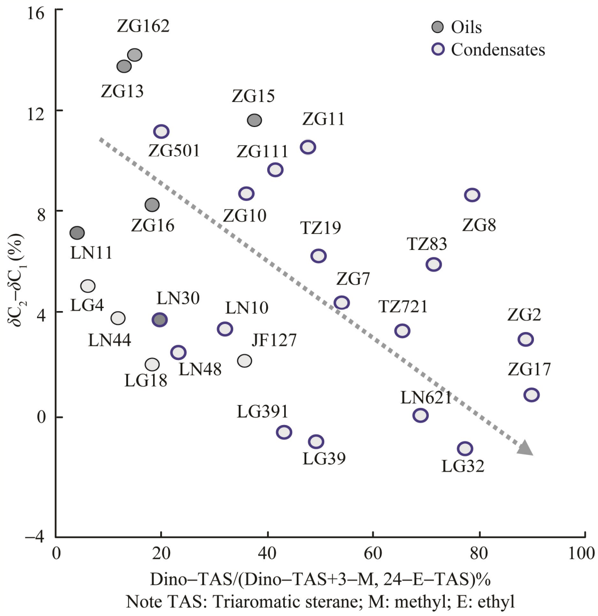

Fig. 2. Increasing contribution of Cambrian SRs to the deep reservoirs with rising maturity and extent of oil-cracking.

al., 2005). Furthermore, the original composition of biomarkers and isotopes in crude oil has also undergone chemical and physical alteration to differing extents. Therefore, it is necessary to further clarify the sedimentary environment and geochemical characteristics of the Cambrian and Ordovician SRs in the Tarim Basin, so as to identify the genetics of the deep hydrocarbons. Arylisoprenoids are considered to be the diagenetic products of biarylcarotene phytols from anaerobic photosynthetic Green Sulfur Bacteria (GSB) and possess exclusive biogenic significance. Therefore, aryl isoprenoids were used to discriminate the source of marine crude oils in the Tarim Craton (Sun et al., 2003). A series of aryl isoprenoids were found in the deep reservoirs of the Tabei Uplift. It is speculated that this type of crude oil would likely be derived from the SRs deposited in a closed euphotic anaerobic environment, which is likely related to the anaerobic sedimentary environment of lower Cambrian SRs, yet not to the suboxic environment of the Upper Ordovician, located in the slope facies of the platform margin. At present, the lower Cambrian SR has been explored in the deepest well, Well LT-1 (8882 m). A series of abundant aryl isoprenoids were also detected in the TOC-enriched siliceous shale of the Yurtusi Formation ($\in_1y$) (Fig. 3), which further confirmed the euxinic environment and provided new geochemical evidence for the prediction of the distribution of deep SRs and the identification of oil sources.

3 Sedimentary Environment and Prediction of the Distribution of the Principal Cambrian and Ordovician SRs

3.1 Lithological assemblage and distribution of Cambrian SRs

The lower Cambrian SRs revealed in the Tarim Basin are mainly developed in the Xishanbulake Formation and the Xidashan Formation ($\in_1x$–$\in_1xd$) in the Manjiaer Sag of the eastern Tarim Basin, as well as the Yurtusi Formation ($\in_1y$) in the center and west of the Tabei Uplift. The $\in_1x$–$\in_1xd$ SRs were sampled via Wells TD-1, TD-2 and ML-1 in the Tadong Uplift. The main lithological assemblage is calcareous, siliceous mudstone and marlstone, generally interbedded with gray-black radiolarian siliceous and overlying the phosphorous siliceous at the bottom (Fig. 4). The total organic carbon (TOC) ranges from 1.1% to 7.8%, the clay mineral content is less than 30%, the quartzite is over 75% and the cumulative thickness of the effective source rocks (TOC ≥ 0.5%) exceeds 150 m. The Xidashan Formation ($\in_1xd$) is in conformable contact with the Xishanbulake Formation, while the mudstone and carbonate are interbedded, the TOC ranging from 0.2% to 5.8% (Fig. 4). The organism precursors of $\in_1x$ kerogen are mainly planktonic algae. Compared with the Xishanbulake Formation, ancient Gloeodiniales appeared in the $\in_1xd$, green algae with cell walls began to flourish and suspected provenances with unclear spherical structures also began to appear (Liu et al., 2016).

The Lower Cambrian Yurtusi Formation ($\in_1y$) SRs have been drilled by Wells XH-1, LT-1 and QT-1 and the Kelpin outcrop in the northwestern Tarim Basin. Lamellar siliceous, siliceous mudstone interbedding, siliceous dolomite and dolomitic fine sandstone were deposited from bottom to top, with barite nodule enrichment (Chen et al., 2015). The average thickness was only 32.7 m (Fig. 5), yet it is a set of SRs with the highest TOC in the lower

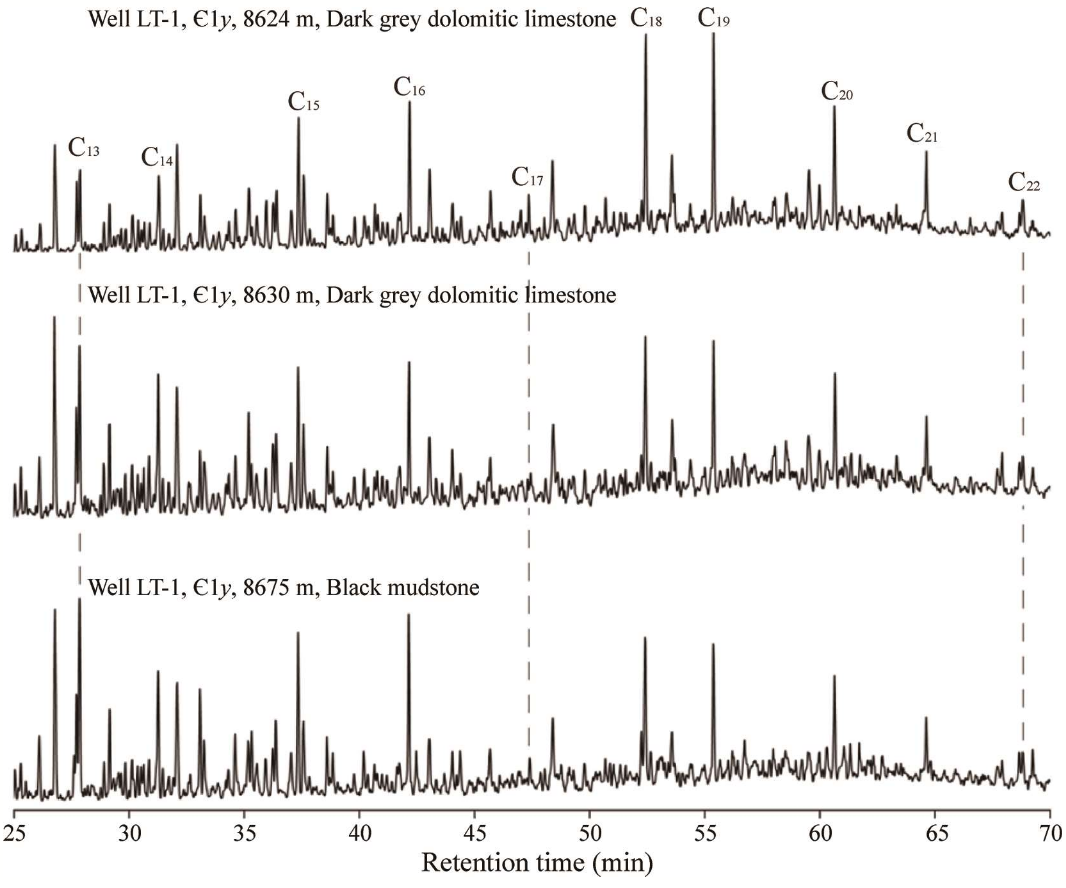

Fig. 3. Distribution of aryl isoprenoids in the lower Cambrian SRs of Well LT–1.

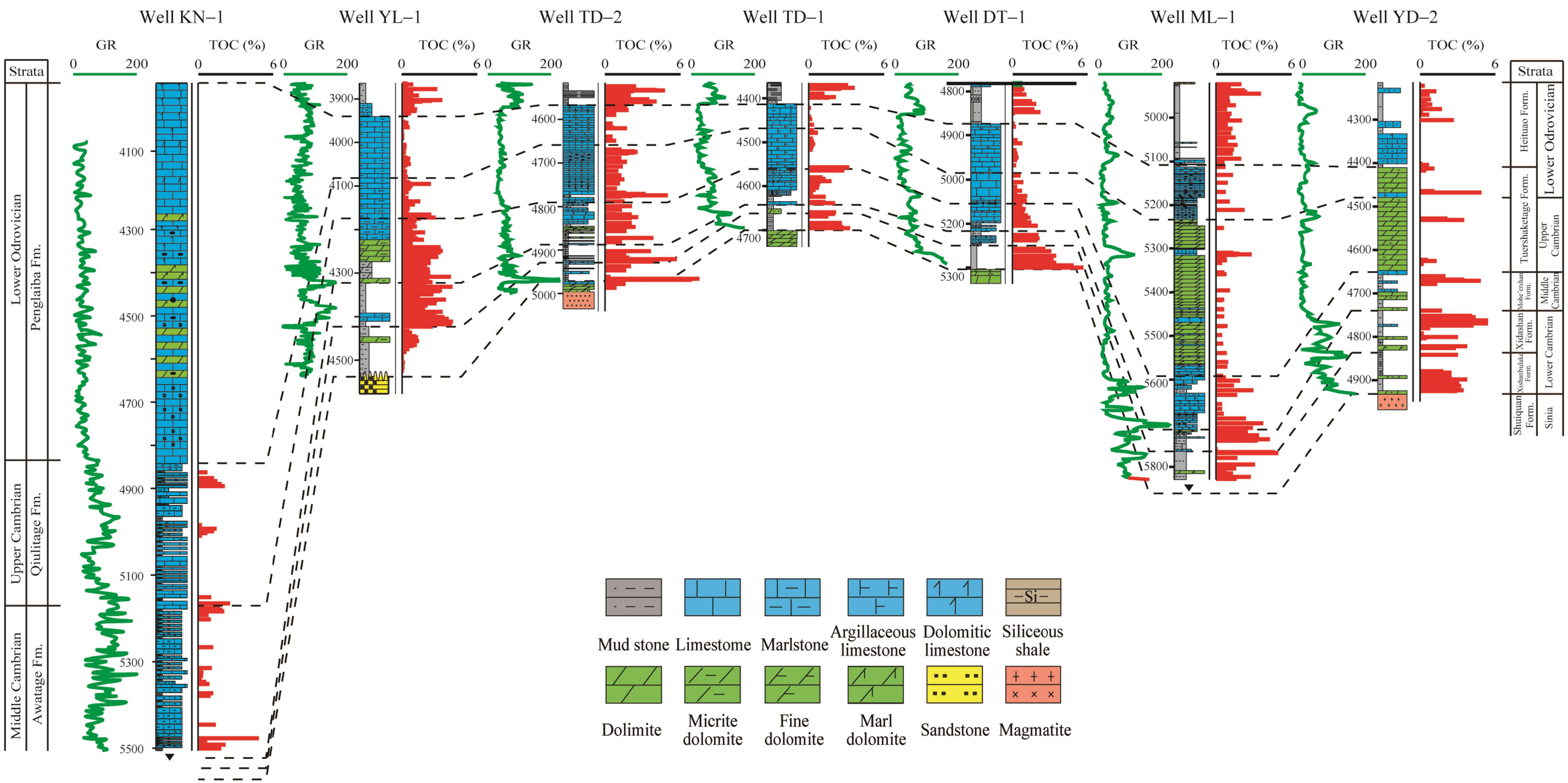

Fig. 4. Correlation profile of lower Cambrian SRs in the Manjiaer Sag, east Tarim Basin.

Paleozoic. The sedimentary sequence of the Yurtusi Formation has undergone two transgressive cycles, forming two layers of TOC-rich mud and shale. The phosphorous siliceous and mudstone interbedding was deposited at the bottom of the transgressive cycle, with the TOC reaching up to 20.6%, averaging 7.3%. The upper transgressive cycle is dolomitic fine sandstone, with low TOC between 0.4% and 1.8% (Fig. 5). In combination with the gravel-sized lithological assemblage and widely-deposited phosphorite in the Yurtusi Formation ($\in_1 y$), it was indicated that the water column gradually evolved from deep to shallow in a relatively high-energy sedimentary environment. The Yurtusi Formation gradually thinned towards the interior of the platform basin, pinching out in the northern margin of the Bachu Uplift. According to the characteristics of the lithology and TOC of the drilled Cambrian SRs, it may be concluded that the Yurtusi Formation ($\in_1 y$) SRs have a cumulative thickness of up to 29 m, with TOC ranging from 0.7% to 13.5%, averaging 6.7%. At the same time, the Xishanbulake Formation ($\in_1 x$) SRs in the eastern Tarim Basin possessed a larger cumulative thickness of up to 70 m, with a relatively low TOC, ranging from 0.52% to 7.8%. The overall distribution of the lower Cambrian SRs in the Tarim Basin is predicted to be more than 20 × 10^4 km^2 (Fig. 5).

3.2 Sedimentary environment and distribution of Ordovician SRs

The δ^{13}C and δ^{18}O curves throughout the entire Ordovician in the Tarim Basin exhibit three obvious excursions (Zhang et al., 2006). The positive excursion of carbon and oxygen isotopes occurred in the Early Ordovician, with the heaviest δ^{13}C value of +1.35‰ and the heaviest δ^{18}O value of −8.2‰. This indicates the process of sea-level regression, with the deposition of the Qiulitage Formation, dominated by dolomite and no SRs. In the initial Middle Ordovician, the δ^{13}C and δ^{18}O exhibited highly negative excursions, the δ^{13}C ranging from −4.6‰ to −8.3‰ and the δ_{18}O at up to −17.1‰. It can thus be inferred that the global sea level rose in the Middle Ordovician, so that the Tarim Basin underwent a

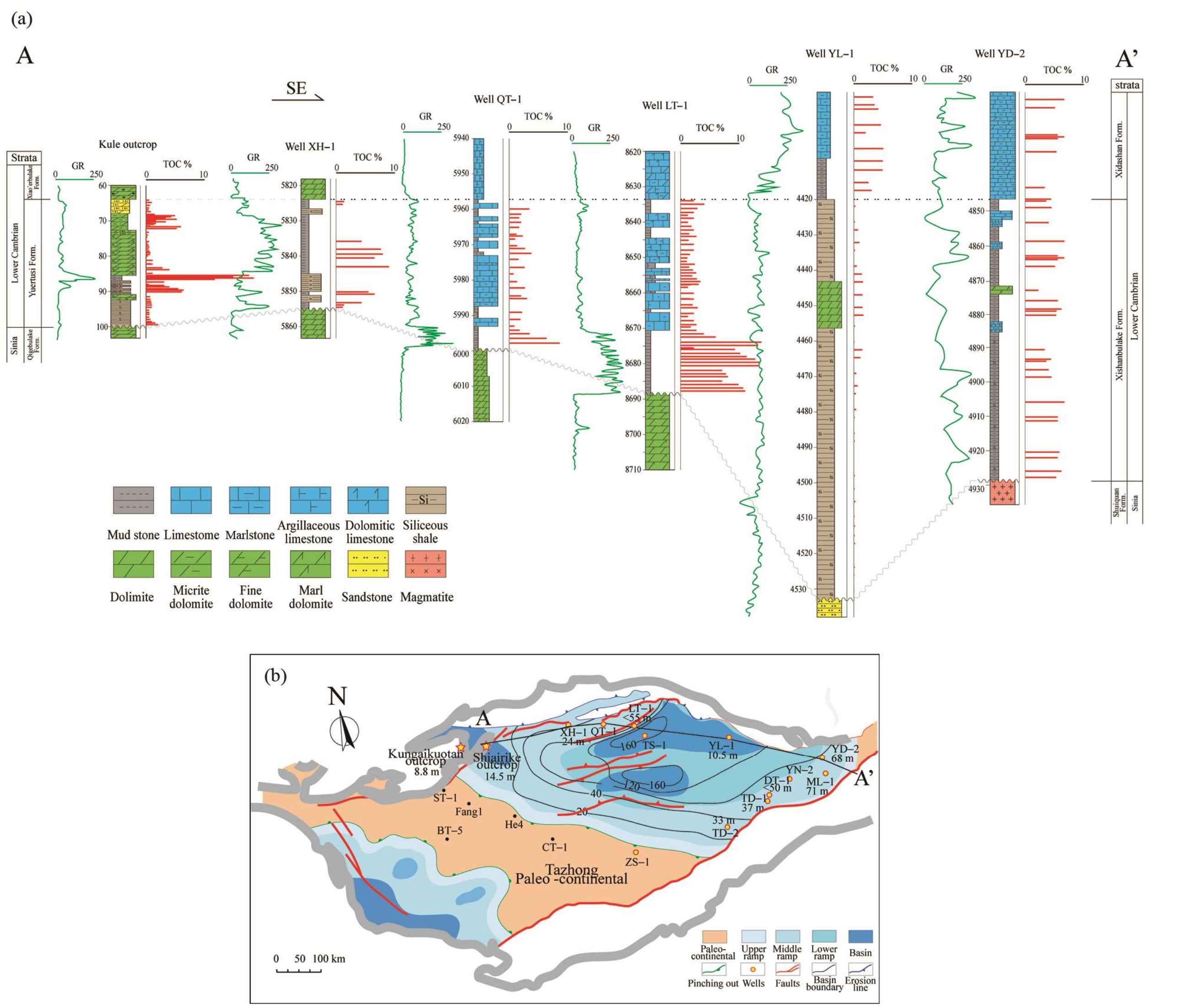

Fig. 5. (a) Sedimentary environment and (b) distribution of the lower Cambrian SRs across the Tarim Basin.

large-scale rapid transgressive process, the Heituao Formation ($O_{1-2}h$) SRs being deposited in the intracratonic depression of the eastern Tarim Basin. The dominant lithology of the Heituao Formation ($O_{1-2}h$) was siliceous shale and black shale, broadly identified in several wells in the eastern Tarim Basin, with a thickness of 48 m in Well TD-1, 56 m in Well TD-2, 161.5 m in Well YD-2 and a maximum thickness of 190.5 m in Well ML-1 (Fig. 6). According to seismic predictions, the Heituao Formation ($O_{1-2}h$) SRs may be thicker in the deposition center of the Manjiaer Sag (Cai et al., 2009; Li et al., 2010). In addition, according to the analysis of core samples from Wells YD-2 and ML-1 of the eastern Tarim Basin, the TOC of $O_{1-2}h$ generally exceeds 1.0%, with the highest value reaching up to 5.8% (Zhang et al., 2004). Meanwhile, the content of free hydrocarbon is higher than the pyrolytic hydrocarbon in the Heituao black shale, with TOC ranging from 1.08% to 2.19% in the Quruqtagh outcrop. Therefore, it is believed that the Heituao shale is one of the most important Ordovician SRs in the eastern Tarim Basin, the predicted distribution area of $O_{1-2}h$ SRs exceeding 8.2 × 10^4 km^2 (Fig. 6).

The Middle and Upper Ordovician SRs discovered in the Tarim Basin mainly include the Saergan Formation ($O_{2-3}s$) in the Awati Sag of the Kelpin outcrop and the Lianglitage Formation (O_3l) in the Awat–Manjiaer transitional zone. The $O_{2-3}s$ black shale was deposited in the northwestern Tarim Basin and formed a rim around the western margin of the Awati–Manjiaer transitional zone (Zhang et al., 2012), with a maximum thickness of approximately 30 m, TOC ranging from 1.2% to 5.6% (Fig. 7). The organism precursors of $O_{2-3}s$ SRs are primarily composed of planktonic algae and acritarchs, including *Eosphaera* and spiny acritarchs, which are symbiotic with graptolites, particularly with reference to *Climacograptusantiquus* and *Dicellograptus*. The presence of *Dicellograptus* indicates that the paleo-water depth of the $O_{2-3}s$ shale deposition was approximately 60 to 200 m (Chen, 1990). In addition, the Charchaqia Formation (O_3q) was another potential Late Ordovician SR with low TOC, mainly composed of turbidite deposits. The formation of O_3q SRs was mainly related to the global hypoxia event, which occurred during the Miaopo period of the Middle Ordovician (Wang et al., 2008).

The Upper Ordovician Lianglitage Formation (O_3l) was primarily composed of argillaceous limestone and marlstone, mainly distributed in the slope of the Tazhong and Tabei uplifts, with a maximum thickness of about 100

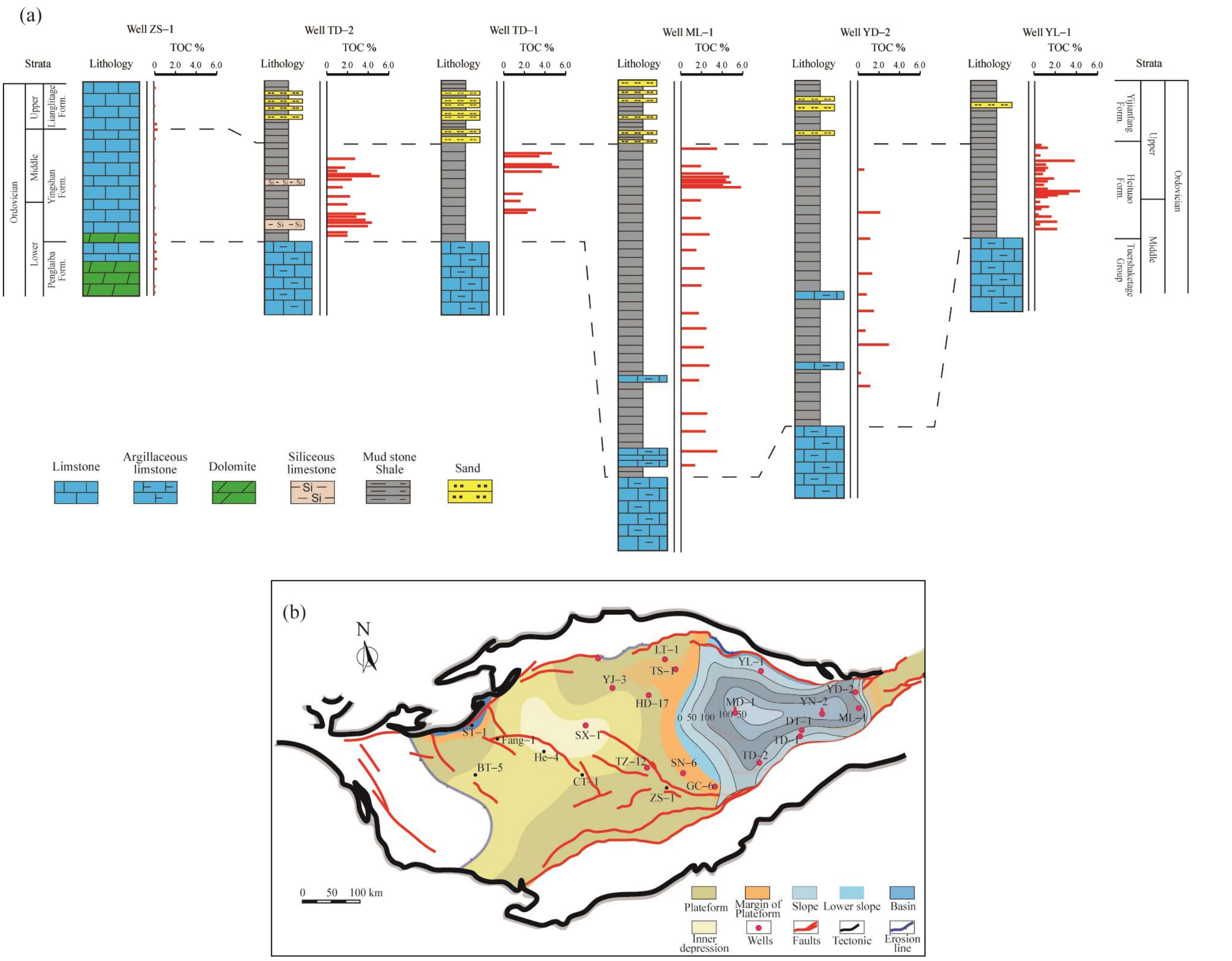

Fig. 6. (a) Correlation of Well section and (b) distribution of $O_{1-2}h$ source rocks of Lower and Middle Ordovician in the Tarim Basin.

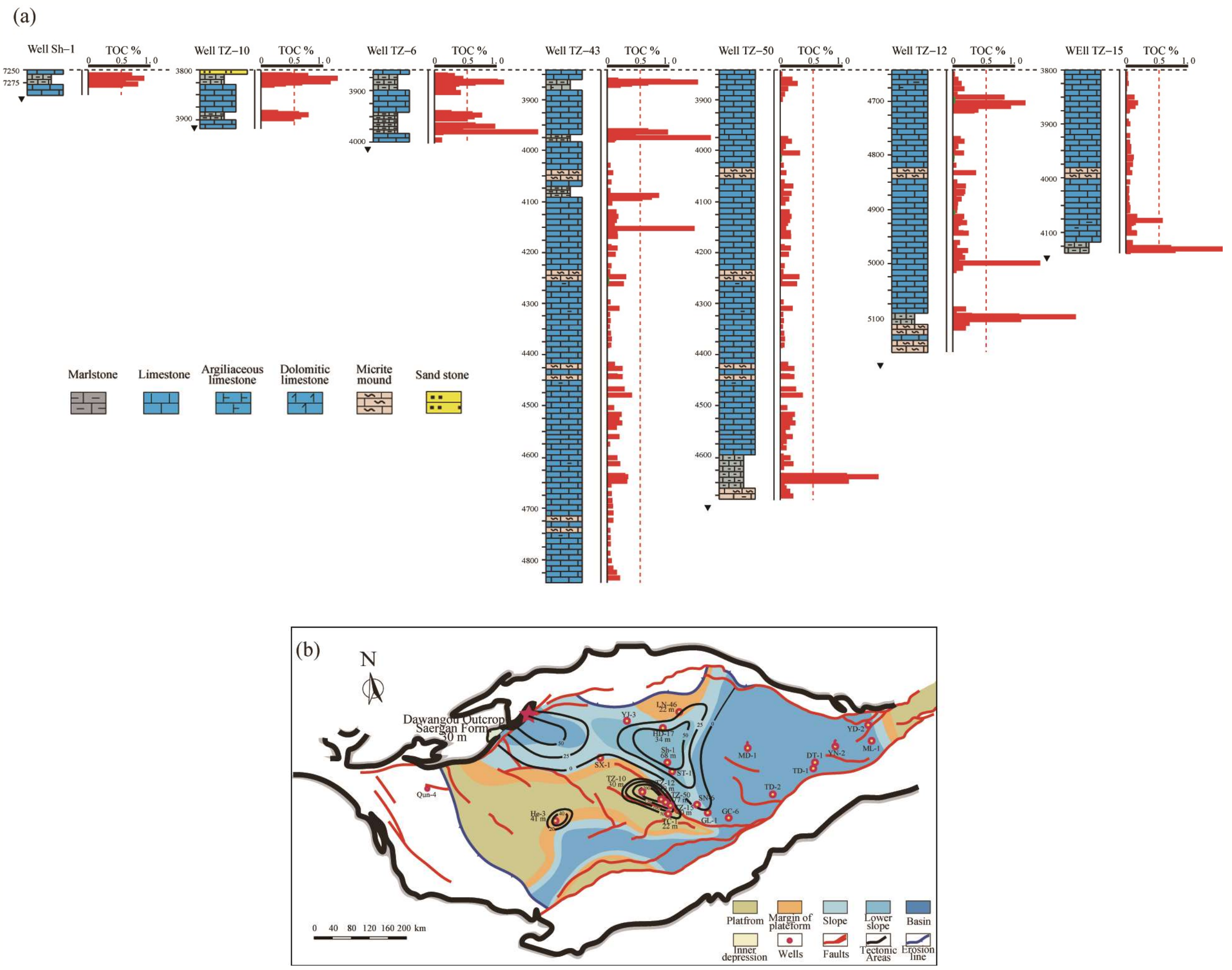

Fig. 7. (a) Correlation of Well section and (b) distribution of Middle and Upper Ordovician ($O_{2–3}s$–O_3l) SRs in the Tarim Basin.

m (Zhang et al., 2004; Li et al., 2010). The TOC of the O_3l SRs in the Tabei Uplift is 0.47%–1.56%, with the thickness of the effective SRs (TOC > 0.5%) being 6–28 m. Around the deep slope of the Tabei Uplift, the highest TOC of the O_3l SRs, from Well HD-17 in the Hade block, could reach as high as 1.7% (Fig. 7).

Throughout the Tarim Basin, the highest TOC of the O_3l SRs reaches 5.44% (Well TZ-201, located at the Tazhong Uplift), with the average TOC being 0.84%. The O_3l SRs thickness is 30–90 m, the cumulative thickness in Well TZ-43 reaching 300 m (Jin et al., 2017). At present, most of the exploration wells have contacted the $O_{2–3}$ SRs of the platform facies, while the high-quality $O_{2–3}$ SRs of the slope facies have yet to be drilled. However, the entire Ordovician in the Manjiaer Sag has undergone multiple transgressions and regressions, multiple overlapping slopes possibly having developed there. It is thus speculated that the better $O_{2–3}$ SRs may deposit in the transitional slope zone from the Tazhong and Tabei uplifts to the Awati and Manjiaer sags. According to the sedimentary setting correlation of TOC and lithological characteristics, it is predicted that the area of the Middle and Upper Ordovician SRs could reach 6.0×10^4 km^2 (Fig. 7)

3.3 Favorable sedimentary facies and depositional environment of the lower Paleozoic SRs in the Tarim Basin

With the breakup of the Pangaea Supercontinent, the global Neoproterozoic large-scale glaciation came to an end and the Laurentia–Siberia continental plate shifted from Antarctica to the lower latitudes. Throughout most of the Cambrian and Ordovician, the Laurentia–Siberia continental plate remained in the tropics, with a warm climate and mostly submerged by seawater, which was conducive to large-scale deposition of SRs. Globally, the Cambrian source rocks were mainly developed in the middle and upper Cambrian (Peters et al., 2005), mostly distributed in the Baltics (Alum Shale Formation), Siberia and North Africa in the middle and high latitudes of the Southern Hemisphere, as well as Australia (middle Cambrian Arthur Creek Formation) near the Equator and adjacent to the Tarim and Yangtze plates. In contrast to the other Cambrian SRs throughout the world, the lower Cambrian SRs in the Tarim Basin were deposited in a tectonic evolutionary background from passive continental margin to intra-platform depression and widely deposited in intracratonic and cratonic margin depressions. It can thus be inferred that the sedimentary environments of the

Cambrian SRs in the Tarim Basin were not only a response to the global climate transition from glacial to greenhouse climate, strong weathering and extensive submarine hydrothermal activity, but were also controlled by the local tectonic sedimentary environment.

After the rapid development of the marine ecosystem in the early Cambrian, the Ordovician SRs were mainly constructed by macro benthic and planktonic algae. Many previous research studies have recognized the similarity between Ordovician SRs and corresponding oils throughout the world, due to the fact that *Gloeocapsamorpha prisca* is the main source biomass for hydrocarbons (Fowler, 1992). The famous kukersite oil shale of the Middle Ordovician in Estonia possesses a high TOC of 40%–50%, up to a maximum of 70% and is mostly composed of *Gloeocapsa*. The Ordovician petroleum system was mainly developed in the Middle–Upper Ordovician and distributed throughout North America, Australia and the Baltic Sea, due to the fact that the largest tectonic transformation occurred in these places in the early Paleozoic. Most of the Ordovician SRs were deposited around paleo-uplifts or slope facies carbonates, including the limestone-calcareous shale of the Middle Ordovician Trenton–Heihe Formation and the Utica/Antes shale of the Upper Ordovician–Silurian in North America. In addition, the frequent fluctuation of global sea level and the collision orogenies of large-scale plates developed several foreland basins and a restricted ocean circulation, which in turn led to anoxic settings around the edge of the tropical-subtropical shelf, effectively conserving abundant algal organic matter (Peters et al., 2005). However, the Ordovician high-quality SRs in the Tarim Basin deposited earlier than those throughout the rest of the world. The highest TOC-rich SRs were concentrated in the Middle and Lower Ordovician Heituao Formation ($O_{1\text{–}2}h$), while the TOC of $O_{1\text{–}2}$ SRs was generally less than 2%, thus indicating that the global climate and local tectonic environment were the key factors impacting the trend of the carbon cycle and the deposition of the Ordovician SRs.

As demonstrated by the global marine source rock sedimentary environment statistics, 73% of large-scale marine SRs are formed in shelf and slope environments (Jin, 2011), most being composed of calcareous or siliceous shale. In particular, slope deposition is located in the transition region between platform and depression, which is beneficial for the supplementation of nutrients and thus prosperous primary productivity. The environment of a closed anoxic, sulfuric and lowest oxygen zone is conducive to the deposition of organic-rich SRs such as limestone, biological limestone and siliceous mudstone. During the Cambrian and Ordovician, the Tarim Basin underwent the transition from passive to active continental margin, structurally evolving from intra-platform depression to platform uplift through four stages of slope evolution (Jin et al., 2009): (1) gentle slope of the early and middle Cambrian carbonate platform; (2) edge slope of the late Cambrian-$_{\text{Early}}$ and Middle Ordovician carbonate platform; (3) slope of the early isolated carbonate platform in the Late Ordovician; and (4) steep slope of the late Paleozoic platform margin. The reconstruction of biological composition and sedimentary environment indicated that the restricted euxinic and deep-water shelf anoxic environment in the gentle slope of the early Cambrian, deep-water shelf in the Early–Middle Ordovician and margin slope environment of the Late Ordovician platform, were mainly conducive to the deposition of the Cambrian–Ordovician SRs in the Tarim Basin (Fig. 8).

The passive continental margin in the late Sinian was inherited and developed in the early Cambrian of the Tarim Basin (Ge et al., 2014). The layered siliceous rocks of the lower Cambrian Yuertusi Formation ($\in_1 y$) and Xishanbulake Formation ($\in_1 x$) recorded hydrothermal activity (Yang et al., 2017), thus reflecting the active tectonic extension in the early Cambrian of the Tarim Basin. Guan et al. (2019) predicted that the thickness of the $\in_1 y$–$\in_1 x$ Yuertusi Formation, which was deposited along the NEE–EW Nanhua–Early Cambrian rift and affected by the synsedimentary tectonic activity in the early Cambrian, would be up to 250 m. However, the Mo/TOC ratioin the black shale of the Yuertusi Formation ranged from 4.97 to 8.11, close to that of the modern Black Sea (4.51) and Framvaren Fjord (9.2) in Norway (Algeo and Lyons, 2006), which demonstrated that the sedimentary hydrology of the Early Cambrian in the northwestern Tarim Basin might not exchange well with the open ocean. This was also consistent with the euxinic environment indicated by the aryl isoprenoids in the $\in_1 y$ black shale. In addition, it is worth noting that the $\in_1 y$ was rich in ^{13}C, while the carbon isotope of kerogen was rich in ^{12}C, resulting in the abnormal phenomenon of isotope reversal. It was inferred that this was related to the transformation of bacteria and microorganisms in the settlement and the diagenesis of organic matter (Zhang et al., 1992). This isotopic reversal of bitumen A and kerogen was prevalent in the Precambrian. The main cause for this lay in the fact that the Precambrian marine ecological community was dominated by ultraplankton, while the microorganisms were degraded by various organisms from the water column to the sedimentary interface (Logan et al., 1995). However, this phenomenon has not been observed in the source rocks of the Xishanbulake Formation. Therefore, it was believed that the underlying lower Cambrian SRs in the Tarim Basin generally deposited at the passive continental margin, with deep-water shelf facies $\in_1 x$ SRs in the eastern part and restricted euxinic slope $\in_1 y$ SRs in the western part.

During the Middle and Late Ordovician, the western Tarim Craton was mainly composed of open platform facies, peripheral foreland basins gradually appearing at the platform margin. At the end of the Ordovician, due to the strong subduction of the Kunlun Ocean and Tianshan Ocean plates on the northern and southern edges of the Tarim Basin, the different settlements resulted in several sets of 'isochronous and heterogeneous' SRs. The $O_{1\text{–}2}$ Heituao Formation was deposited in the deep-water shelf of the Manjiaer Depression and possessed the highest TOC, reaching up to 4.33%. The $O_{1\text{–}2}h$ SRs were mainly thin-layer siliceous mudstone intercalated with radiolarian bedded chert, the hydrocarbon-generating organisms mostly consisting of planktonic algae and

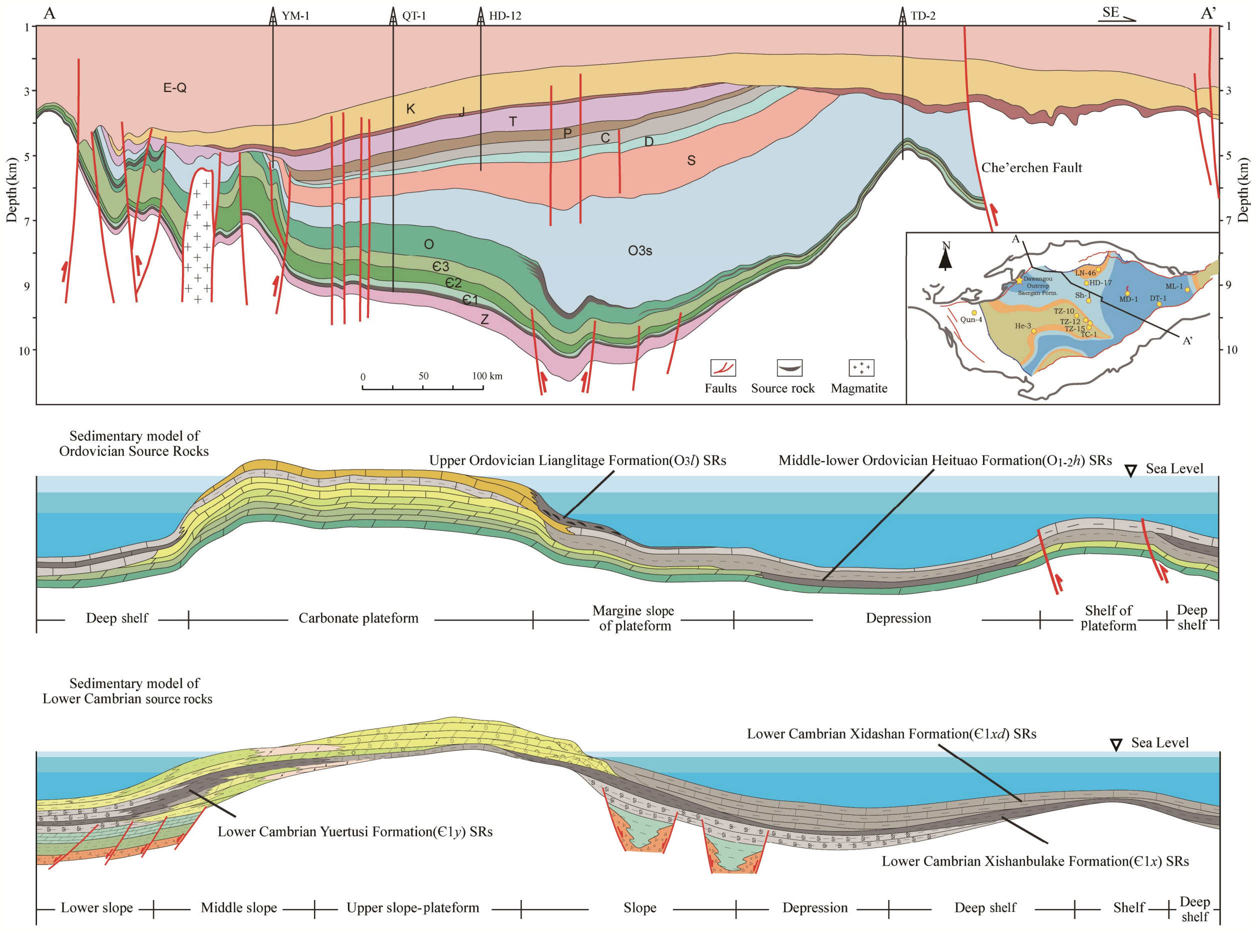

Fig. 8. Comparison of geological profiles and sedimentary environments of Cambrian-Ordovician SRs in the Tarim Basin.

Volvox, which belonged to typical deep-water shelf-basin deposition (Fig. 8). The $O_{2-3}s$ shales were developed in the Middle and Upper Ordovician of the Tarim Basin. According to the lithological and paleontological fossil records, it could be inferred that $O_{2-3}s$ shales were deposited in the restricted deep-water shelf (Fig. 8). Spherical pyrite nodules were common in the calcareous shale of the $O_{2-3}s$ shales. Specifically, the value of $\delta^{34}S$ was −26.8‰, which is strongly negative compared with that of the Ordovician initial seawater (Claypool et al., 1980), indicating an under-compensated reducing environment. Two types of hydrogen-rich and hydrogen-poor macerals were developed in the Upper Ordovician Lianglitage Formation (O_3l) SRs, coexisting in a relatively reduced sedimentary environment. Phytoplankton and shallow benthic thalli were the major primary producers in the ecosystem of O_3l SRs, while planktonic algae and acritarchs constituted the fluorescent hydrogen-rich organic matter in the O_3l SRs, including the most important Ordovician organisms, such as *Gloeocapsamorpha prisca* (Zhang et al., 2002, 2004). On the other hand, benthic thalli contributed to the presence of the marine vitrinite in the O_3l SRs (Wang et al., 2001). This ecosystem originated in the Neoproterozoic and prevailed in the shallow sedimentary environment of the platform margin. At the end of the Late Ordovician, with the rise of the sea level, the platform of the Tarim Craton submerged, resulting in the end of the deposition of the Ordovician SRs (Fig. 8).

4 Exploration Objectives for the Deep Reservoirs in the Tarim Basin

4.1 Contribution of Cambrian−Ordovician SRs to the accumulation of deep reservoirs

With its low TOC abundance and distribution area, the hydrocarbon-generating intensity of the Ordovician SRs was estimated at over 250×10^4 t/km^2 (Fig. 9), while the total hydrocarbon reserve equivalent of the Ordovician SRs is 2,42 0 $\times 10^8$ t, only 1/3 of the total reserve of the Cambrian SRs. The ∈–O_1 SRs have relatively high contents of triaromatic dinoflagellate sterane, which clearly indicates the biogenic contribution of diatoms and dinoflagellates (Hanson et al., 2000; Zhang and Huang, 2005; Yu et al., 2011). Based on the ratio of triaromatic dinoflagellate sterane/(triaromatic dinoflagellate sterane+ 3β-methyl-24-ethyl-triaromatic cholestane), the reservoirs in the Tazhong Uplift were generally mixed sources, the contribution being roughly equivalent. The hydrocarbons in the Tabei Uplift were mainly derived from the Ordovician SRs. The hydrocarbon contribution of the Cambrian source rocks accounted for the reservoirs in the

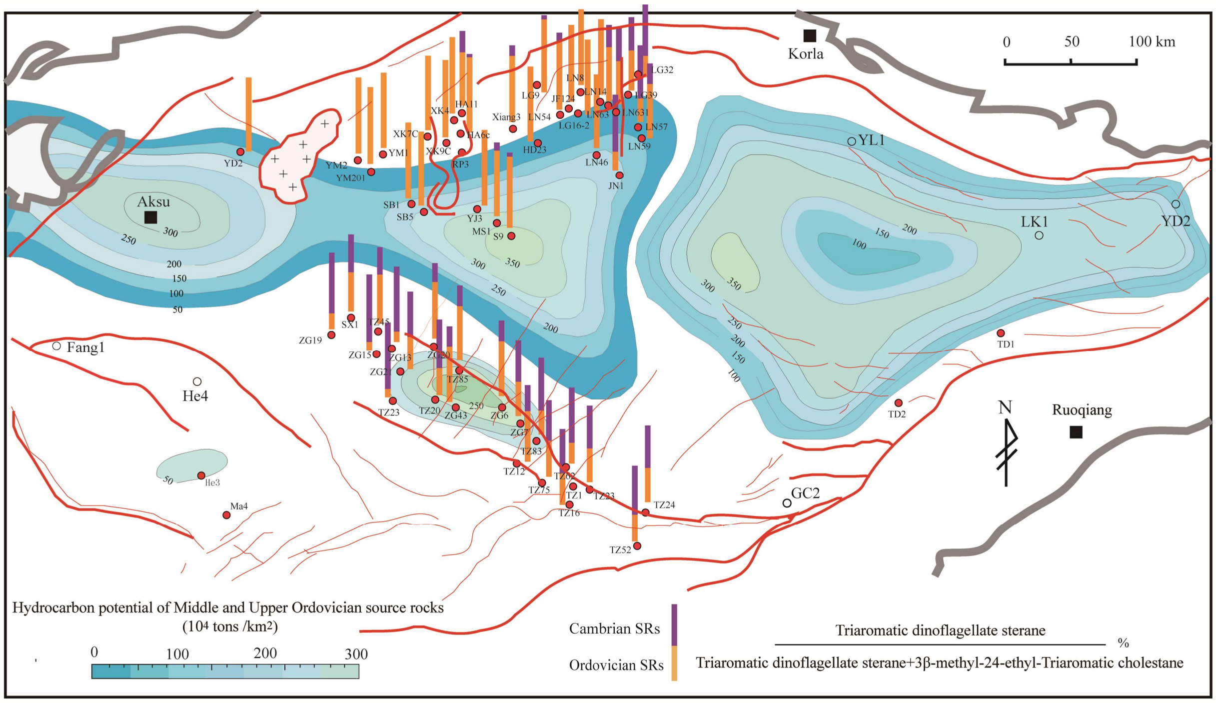

Fig. 9. Distribution of hydrocarbon-generation intensity and the hydrocarbon contribution of Ordovician SRs in the Tarim Basin.

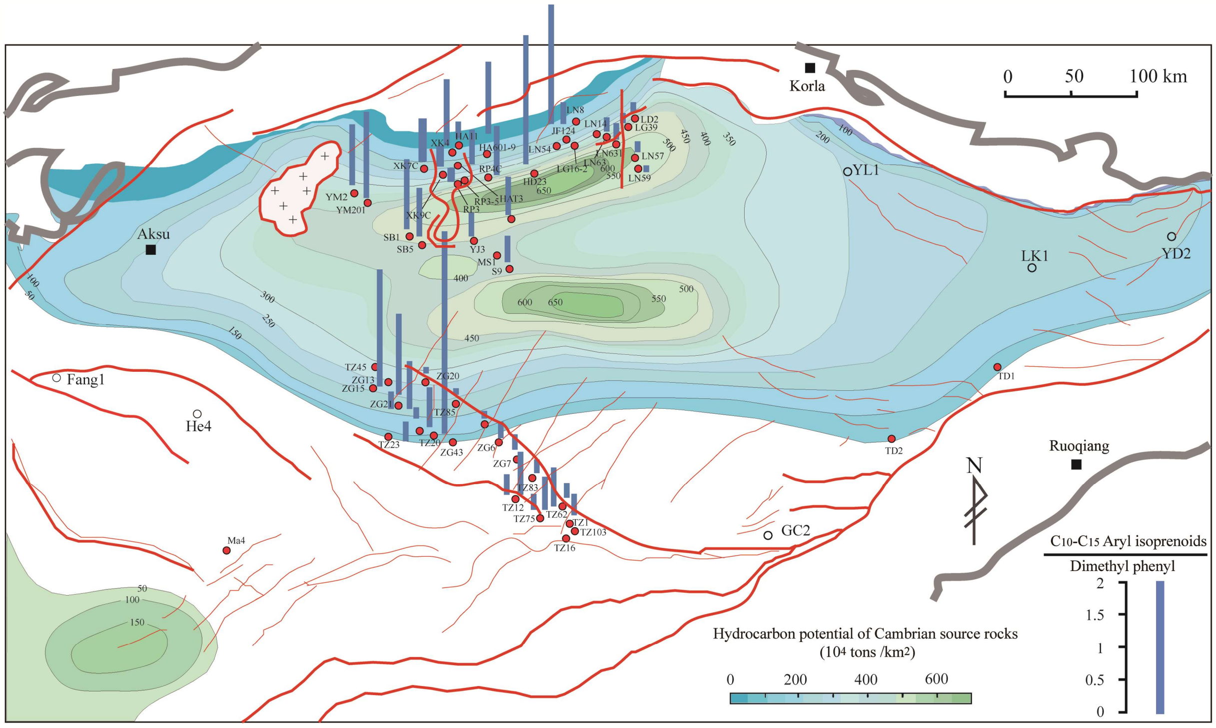

Fig. 10. Distribution of hydrocarbon-generation intensity and hydrocarbon contribution of lower Cambrian SRs in the Tarim Basin.

Lungudong area of the east Tabei Uplift and near the Halahatang fault zone (Fig. 9). With exploration expanding in the slope of the Tabei Uplift, triaromatic dinoflagellate sterane was absent from the deep reservoirs, thus can not be used to determine the main source for the deep hydrocarbons, so an accessory proxy for oil-source correlation should be considered.

Meanwhile, Cambrian SRs would be the potential main source for deep hydrocarbons, based on the tectonic depth. According to the distribution area, TOC abundance, thickness, evolutionary maturity and hydrocarbon generating potential (500 mg/g TOC) of the lower Cambrian SRs in the Tarim Basin, it is estimated that the hydrocarbon generation intensity of Cambrian SRs could exceed 450×10^4 t/km^2 (Fig. 10) and the equivalent hydrocarbon reserve of the entire Cambrian SRs is approximately 7,500 × 10^8 t. A series of abundant aryl isoprenoids were also detected in the TOC-enriched siliceous shale of the Yurtusi Formation ($\in_1 y$) (Fig. 3), which further confirmed the euxinic environment and provided new geochemical evidence for the prediction of the distribution of deep SRs and the identification of oil sources. In contrast, aryl isoprenoids were absent from the Xishanbulake and Xidashan formations of the lower Cambrian ($\in_1 x$–$\in_1 xd$). The distribution characteristics of lower Cambrian SRs could be utilized to discriminate the hydrocarbons derived from $\in_1 x$–$\in_1 xd$ and $\in_1 y$ SRs. Based on the ratio of phenylisoprene to dimethylbenzene, the contribution of $\in_1 y$ and $\in_1 x$ source rocks in the Tarim Basin to the lower Paleozoic reservoirs could be effectively divided. It can be seen that the oils in the central and western Tabei Uplift and the northern slope of the Tazhong Uplift were mainly derived from $\in_1 y$ SRs deposited in an euxinic environment; the easternmost part of the Tabei Uplift and the mid-eastern part of the Tazhong Uplift were mainly related to $\in_1 x$–$\in_1 xd$ deep-water anaerobic deposition (Fig. 10).

The discrimination of hydrocarbon sources based on correlation indices exhibiting marine hydrocarbons in the Tarim Basin were mainly derived from the mixture of the Upper Ordovician and lower Cambrian SRs (Fig. 10). Meanwhile, the hydrocarbons of western lower Cambrian slope SRs mainly distributed around the middle–western Tabei Uplift and the hydrocarbons of eastern lower Cambrian deep-shelf SRs, mainly contributed to the reservoirs in the east of the Tabei and Tazhon uplifts. By comparing the distribution area, thickness, TOC abundance and hydrocarbon generating intensity of the Cambrian and Ordovician SRs in the Tarim Basin, it could be estimated that the hydrocarbon resources of the Cambrian SRs exceeded the Ordovician SRs. Therefore, the Cambrian–Ordovician slope SRs would be the main SRs for the deep reservoirs in the Tarim Basin and in particular the Cambrian SRs must be the key field for deep exploration.

4.2 Hydrocarbon generation of Cambrian–Ordovician SRs

Many previous research studies have focused on the paleo-geotemperature in the Tarim Basin. Zhou and Sheng (1986) adopted the Loptin–Waples procedure to reconstruct the evolution of paleo-geotemperature, proposing that the geothermal gradient of the Tarim Basin in the early Paleozoic was about 35 °C/km. Qiu et al. (2012) comprehensively calibrated the tectono-thermal evolution of the Tarim Basin during the early Paleozoic, according to the apatite fission track and (U-Th)/He ages of zircon, in combination with the equivalent vitrinite reflectance. The simulation exhibited the differences of Paleozoic thermal evolution between northeast Tarim and the Bachu Uplift. The paleo-geothermal gradient of the Bachu Uplift was only 28–30 °C/km at the end of the Cambrian, which then increased to 30–33 °C/km in the Ordovician, reaching 31–34 °C/km in the Silurian and Devonian. The geothermal gradient of the northeast Tarim Basin was 35 °C/km in the Ordovician and 32–35 °C/km in the Silurian and Devonian. Therefore, the hydrocarbon generation and maturity evolution of the Cambrian–Ordovician SRs in different tectonic units could be quantitatively restored.

The Tarim Basin has undergone three major tectonic activities, resulting in a ‘three uplifts and four depressions’ tectonic configuration for the Tarim Basin, with commonly two types of hydrocarbon generation evolution in the depression unit and slope unit (Fig. 11). The Tarim Basin was characterized by being thick in the lower Paleozoic and Cenozoic, while relatively thin in the upper Paleozoic and Mesozoic. These tectonic characteristics led to early and rapid hydrocarbon generation of $O_{1-2}h$ and $\in_1 x$–$\in_1 xd$ SRs in the depression of the Tarim Basin, which reached the stage of the oil generation window in the late Caledonian, at which point it rapidly completed gas generation. The equivalent vitrinite reflectance of $O_{1-2}h$ and $\in_1 x$–$\in_1 xd$ SRs was more than 1.5% (VR_o^E) in the late Caledonian. From the late Caledonian to the early Hercynian, the Tarim Basin underwent intense uplift and denudation, the paleo reservoirs accumulated in the late Caledonian being dramatically destroyed and biodegraded. The widely-distributed Silurian bituminous sand and reservoir bitumen were mostly generated during this stage. In the subsequent Hercynian, the Tarim Basin subsided again, the depth increasing. The maturity of $\in_1 x$–$\in_1 xd$ and $O_{1-2}h$ SRs in the depression reached 2.0% (VR_o^E) at the end of the late Hercynian and basically lost its capacity for large-scale hydrocarbon generation. At present, the temperature of SRs in the depression is generally over 200°C and the equivalent vitrinite reflectance is higher than 2.4% (VR_o^E). The thermal maturity in the center of the Manjiaer Depression is the highest, at 4.0% (VR_o^E), followed by the Awati depression, being generally above 3.2% (VR_o^E). The thermal maturities of the Tanggu depression and the southwestern depression are slightly lower than those of the Manjiaer and Awati depressions, being in the maturity range of 1.6%–2.4% (VR_o^E), mainly involving the generation of light oil, condensate and cracking gas (Fig. 11).

The depth of $\in_1 y$ and $O_3 l$ SRs in the slope of the paleo-uplift is at least 2,000 m shallower than that of the contemporaneous SRs in the depression, their tectonic subsidence being relatively slow. In the late Caledonian, they successively began to reach the oil generation window. The entire Paleozoic source rocks in the slope have remained in the ‘oil generation window’ (VR_o^E range 0.6%–1.2%), where they have acted as the main source for liquid hydrocarbons in the paleo-uplift. In the late Hercynian, the geothermal gradient was higher than 30°C/km, due to volcanic activity. The $\in_1 y$ SRs were much older and deeper than the $O_3 l$ SRs, thus the $\in_1 y$ SRs would take the lead in reaching the post-high mature level ($VR_o^E > 1.3\%$), while the maturity of the $O_3 l$ SR continued to evolve and reach the peak of hydrocarbon generation (Fig. 11). During the Himalayan, the Kuqa foreland rapidly collided and uplifted, in turn resulting in the rapid subsidence of the Tabei Uplift and the cracking of liquid hydrocarbon, without completing or reaching equilibrium. Therefore, the cracking gas was only charged in the Lungudong slope of the Tabei Uplift, the large-scale oil cracking not occurring in the deep slope surrounding the paleo-uplift. In other words, the Cambrian–Ordovician SRs in the slope would have been the main source for large-scale deep resources in the Tarim Basin.

The multi-stage hydrocarbon generation of the Cambrian–Ordovician SRs in the Tarim Basin not only resulted in the accumulation of large-scale mixed-source oils, but also led to the production of cracking gas in the late stage. Various properties of hydrocarbons and complex reservoirs accumulated in the superimposed petroleum systems. As shown by the accumulated evolutionary profiles of hydrocarbons in the Tarim Basin, two paleo-uplifts became the favorable accumulation positions in the late Hercynian. The depth of the Tabei Uplift was relatively shallow compared to the Tazhong Uplift, resulting in more hydrocarbons being accumulated in the Tabei Uplift. Due to poor preservation in the high position, some paleo-reservoirs were damaged and biodegraded, so that the heavy oil and bitumen sand were

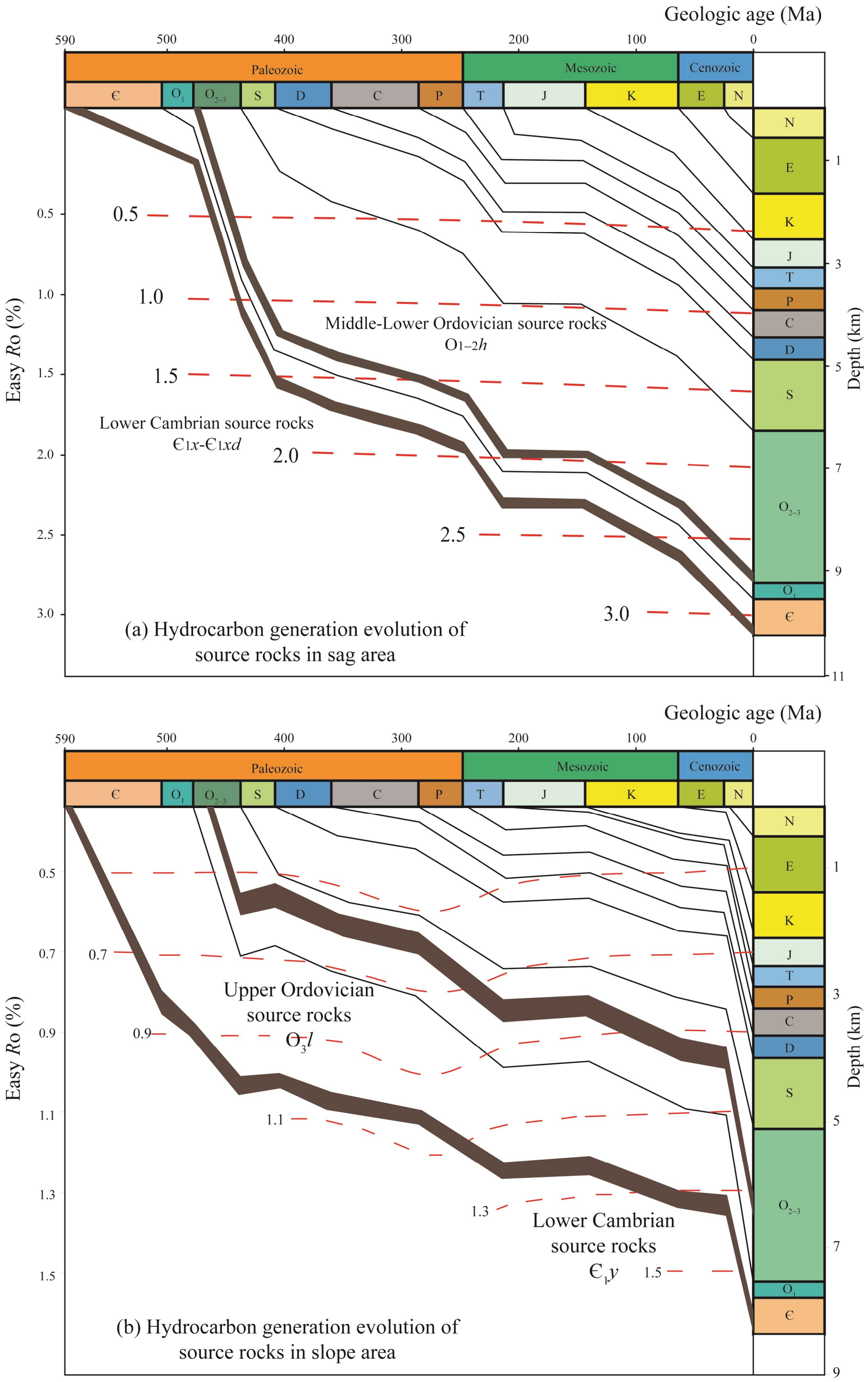

Fig. 11. Comparison of thermal evolution of hydrocarbon generation from source rocks in (a) the slope and (b) the depression of the Tarim Basin.

residual. As early as the late Caledonian, the Cambrian and Ordovician SRs in the depression had been high-post mature. The cracking gas mainly accumulated surrounding the hydrocarbon source, transported and charged to the adjacent Tazhong paleo-uplift, then mixed with the early paleo-reservoir (Fig. 12b).

Since the late Himalayan (23 Ma), the collision activity of the Kuqa foreland has caused the strata above the Carboniferous in the Tabei Uplift to lean southward. Subsequently, the Tabei Uplift was buried rapidly and deeply, the slope of the paleo-uplift gradually becoming the neo-uplift in the northern Tarim Basin. Later, the early oil reservoirs were adjusted and re-accumulated. Meanwhile, due to the high burial rate, the oil reservoirs did not undergo significant cracking, thus the deep reservoirs in the Tabei Uplift still preserved their liquid phase (Fig. 12a). In contrast, the source rocks in the depression had already reached the post-mature stage, generally contributing cracking gas to the deep reservoirs. The cracking gas mainly migrated and accumulated near the Tahzong Uplift along the NE faults, finally leading to the distribution pattern of deep oil reservoirs in the Tabei Uplift, along with cracking gas and condensate enrichment in the slope of the uplifts (Fig. 12a).

4.3 Platform margin slope area conducive to deep marine oil and gas enrichment

The recent exploration of marine reservoirs in the Tarim Basin has led to three main breakthroughs: (1) The quasi-stratified hydrocarbon-rich reservoirs in the Yijianfang Formation–Yingshan Formation (O_2y–$O_{1–2}y$) of the Tabei Uplift were confirmed. At present, more than 100 million tons of geological reserves have been identified in the Shunbei block, located on the south slope of the Tabei Uplift. In 2020, Well MS-1, on the western slope of the Manjiaer Depression, was drilled. A commercial reservoir has been revealed at a depth of nearly 8,000 m, the daily oil yield being 624 m^3 and the natural gas output being 37.1×10^4 m^3/d. The respective oil-bearing potential in the slope belts of the Tabei and Tazhong uplifts can thus be observed. (2) The discovery of the lower Cambrian gypsum-salt related reservoirs has clarified the distribution of Cambrian SRs and deep hydrocarbon resources. In 2013, the industrial reservoirs were first discovered under the Cambrian salt in the Xiaoerbulake Formation and the inter-salt Awatag Formation of the Tazhong Uplift, which indicated the hydrocarbon potential of the Cambrian SRs. However, subsequent exploration in the Cambrian had basically failed, until high gas-bearing reservoirs were discovered in the Keping area of the western Aksu depression in 2019, the $\in_1y$ SRs having been determined as the source for the reservoir in the Wusonggeer Formation ($\in_1w$). Later, another deep reservoir in the $\in_1w$, at a depth of over 8,200 m, was uncovered via Well LT-1, of which the daily oil yield was 133.46 m^3 with a natural gas output of 4.87×10^4 m^3/d. This not only promoted confidence in deep exploration, but also demonstrated the presence of high-quality SRs in the lower Cambrian. (3) The Cambrian interior dolomite reservoir was also one of the fields with the most potential for deep exploration. In 2016, the lower Qiulitage Formation ($\in_3q$) reservoir in Well ZG-58, located in the eastern Tazhong Uplift, exhibited hydrocarbon properties similar to those in the Shunnan and Gucheng blocks, thus indicating the prospective potential of high-post mature cracking gas in the deep strata of the eastern Tarim Basin.

Through the above exploration discoveries and geological analysis, it can be concluded that the Cambrian–Ordovician high-quality SRs were mainly deposited in the gentle slope and deep-water shelf of the paleo-uplift, platform and passive continental margin in the Tarim Basin. The $\in_1x$–$\in_1xd$ slope facies, $O_{1–2}h$ deep-water shelf and O_3l platform margin slope facies were the major sedimentary environments surrounding the Manjiaer Depression in the Tarim Basin. The favorable deep exploration fields mainly include the southeast slope of the Tabei Uplift and the northeast slope of the Tazhong Uplift (Fig. 13). The south slope of the Tabei Uplift was a profitable slope for SR deposition in the early Cambrian, subsequently developing carbonate reservoirs at the platform margin in the early Paleozoic, such as fracture-lithological traps and interlayer karst in the dolomite-limestone strata. In the late Himalayan, the Cambrian–Ordovician carbonate reservoirs were rapidly buried, hydrocarbons being adjusted and re-accumulated. The south slope of the Tabei Uplift was adjacent to the hydrocarbon source in the northern depression of the Tarim Basin, while the faults and unconformities acted as the contemporaneous migration channel of petroleum, which matched closely with the tectonic uplift. Three major types of exploration fields can be identified. The $\in_{1–2}$ oil-bearing dolomite reservoir assemblage and $O_{1–2}$ karst oil-rich reservoirs (Fig. 12). The inherited paleo-uplift developed in the Tazhong Uplift, located relatively far from the hydrocarbon source in the moderately mature slope and near the high-post mature SRs in the eastern depression of the Tarim Basin. The Tazhong Uplift mainly underwent mixed accumulation of high-over mature cracking gas and early reservoirs. The NE-trending strike slip fault was the main transportation system (Zhang et al., 2020), particularly affecting the migration and distribution of the late cracking gas. Furthermore, the NE-trending strike slip fault connected the hydrocarbon sources and reservoirs of the Lower Ordovician–Cambrian dolomite and granular beach, thereby constructing another favorable deep exploration field around the platform margin. Therefore, the south slope of the Tabei Uplift and the northern slope of the Tazhong Uplift surrounding the Manjiaer Depression would be the most important targets for deep exploration, as well as the most realistic favorable exploration fields for large- and medium-scale reservoirs. In particularly, the oil-cracking gas would be a significant potential reserve around the western margin of the Manjiaer Depression, accumulated in the Lungu and Gucheng areas along the lower slope of the Cambrian Platform (Fig. 13).

5 Conclusions

(1) The origin of marine oils in the Tarim Basin is a long-term controversial issue. The high-over mature SRs and complex secondary alterations further complicate the interpretation of oil-source correlation. Along with the development of deep marine reservoirs, hydrocarbon

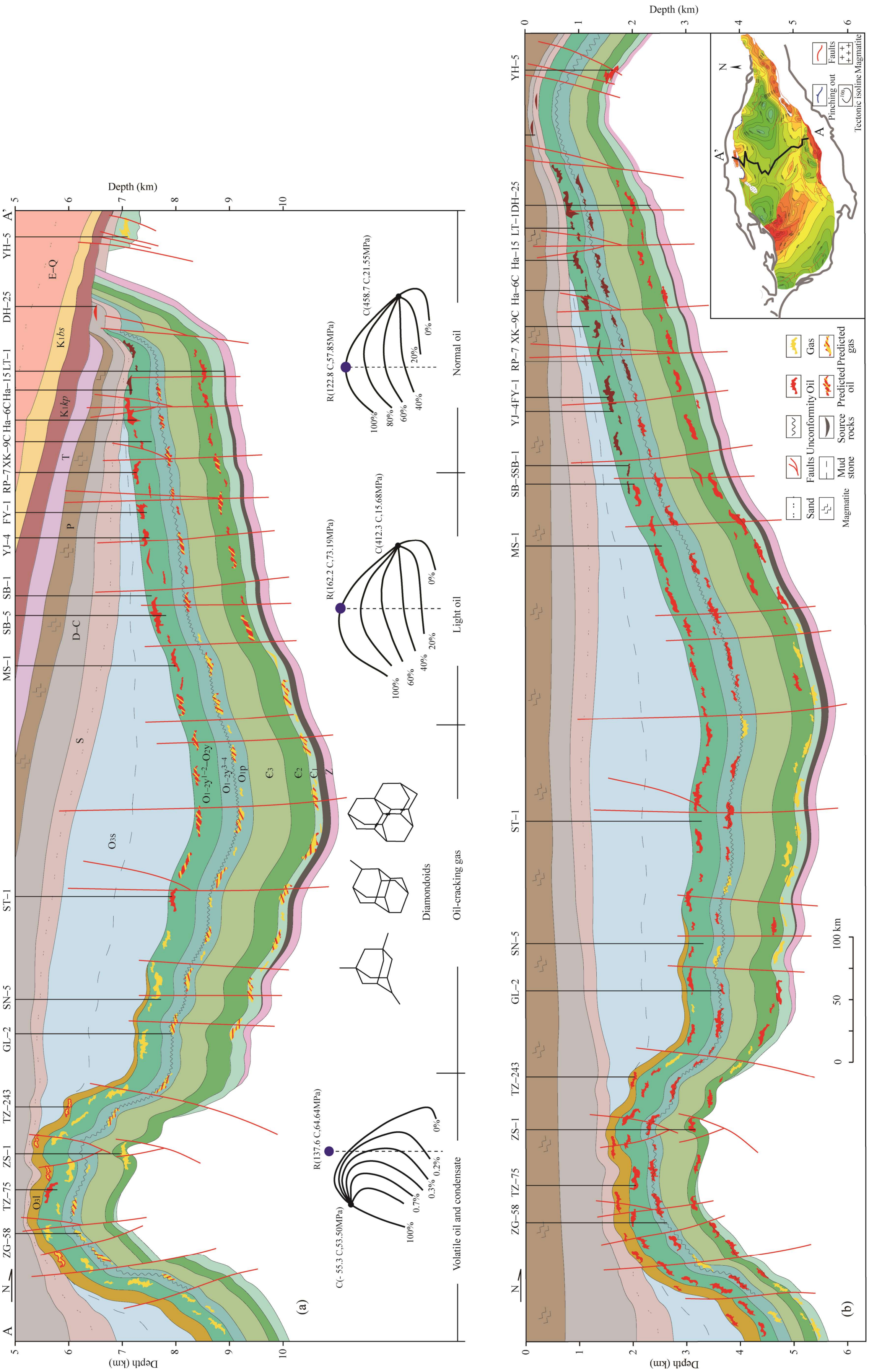

Fig. 12. NS-trending geological section of accumulation evolution of various complex reservoirs in the Tarim Basin. (a) Distribution and prediction of deep reservoirs in the Tarim Basin at present; (b) hydrocarbon accumulation of paleo-reservoirs in the Tarim Basin in the late Hercynian.

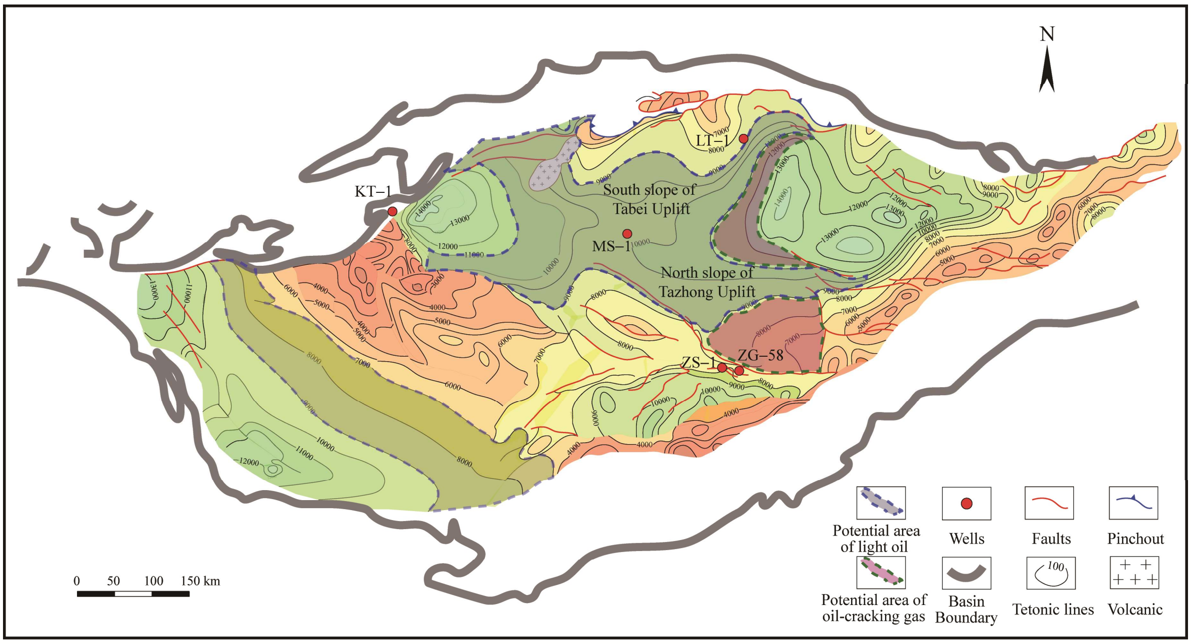

Fig. 13. Predicted favorable exploration areas for deep carbonate reservoirs in the Tarim Basin.

exploration extends to the middle–lower Ordovician and lower Cambrian. According to the oil-source correlations based on TMAIs and triaromatic steranes, it can be seen that the hydrocarbons possess an obviously mixed origin of Cambrian–Ordovician SRs. With the increasing reservoir depth, the contribution of Cambrian SRs to deep hydrocarbons gradually increases.

(2) During most of the Cambrian and Ordovician, the climate was generally warm, most of the craton basin being submerged under seawater, which was conducive to the deposition of large-scale SRs. Through analysis of the biological precursors and sedimentary environment, it was concluded that the Cambrian–Ordovician SRs in the Tarim Basin were controlled by the evolution of the paleo-ocean, tectonic activities and the carbon cycle, also dependent on the enrichment and preservation of organic matter by local sedimentary conditions. Most of the high-quality marine SRs in the Tarim Basin were deposited in the margin slope of passive continental and deep-water shelf facies around the platform. The lower Cambrian $\in_1 y$ in the western Tarim Basin was affected by obvious hydrothermal activity and was mainly deposited in the sulfide anaerobic setting on the lower slope. Meanwhile, the lower Cambrian $\in_1 x$–$\in_1 xd$ in the eastern Tarim Basin was deposited in the deep-water shelf anoxic environment, the overall area of the lower Cambrian SRs being more than 20×10^4 km^2. The overall area of the deep-water shelf $O_{1-2}h$ and the Upper Ordovician slope facies $O_3 l$ SRs was approximately 14×10^4 km^2. The contribution of lower Cambrian SRs to marine deep reservoirs is greater than that of the Ordovician SRs. It is thus speculated that the Cambrian reservoirs surrounding the Tabei Uplift will likely be the key field objectives for further deep exploration.

(3) According to the recent discoveries in deep exploration and geological research, the thermal evolution of SRs in the slope zone has been shown to be basically consistent with the formation of hydrocarbon traps, which is more favorable to the preservation of deep reservoirs than the hydrocarbon generated within the depression area. The rapid and deep burial in the late stage did not cause large-scale oil cracking in the slope belt of the paleo-uplift. Among the favorable slope zones of deep exploration, the southern slope of the Tabei Uplift was the SRs' sedimentary position, as well as the development area of the carbonate fracture-lithological traps. The hydrocarbons mainly migrated along the lateral unconformities and were supplemented by vertical faults, thus forming three major types of exploration fields: middle and lower Cambrian salt bed-related oil-bearing; inner reservoirs in the dolomite assemblage; and middle and lower Ordovician hydrocarbon-rich karst reservoirs. In the future, these will become the most favorable directions in which to pursue marine deep exploration in the Tarim Basin.

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References

Algeo, T.J., and Lyons, T.W., 2006. Mo–total organic carbon covariation in modern anoxic marine environments: Implications for analysis of paleoredox and paleo hydrographic conditions. Paleoceanography, 21(1): 1–23.

Cai, C.F., Zhang, C.M., Cai, L.L., Wu, G.H., Jiang, L., Xu, Z.M., Li, K.K., Ma, A.L., and Chen, L.X., 2009. Origins of Palaeozoic oils in the Tarim Basin: Evidence from sulfur isotopes and biomarkers. Chemical Geology, 268: 197–210.

Cai, C.F., Zhang, C.M., Worden, R.H., Wang, T.K., Li, H.X., Jiang, L., Huang, S.Y., and Zhang, B.S., 2015. Application of sulfur and carbon isotopes to oil–source rock correlation: a case study from the Tazhong area, Tarim Basin, China. Organic Geochemistry, 83–84: 140–152.

Chen, X., 1990. Graptolite depth zonation. Acta Palaeontologica Sinica, 29(5): 507–526.

Chen, Q.L., Yang, X., Chu, X.L., Hu, G., and Shi, Z., 2015. Recognition of depositional environment of Cambrian source rocks in Tarim Basin. Oil & Gas Geology, 36 (6): 880–887.

Fowler, M.G., 1992.The influence of *Gloeocapsomorpha prisca* on the organic geochemistry of oils and organic-rich rocks of Late Ordovician age from Canada. In: Schidlowski, M., Golubic, S., Kimberley, M.M., McKirdy Sr., D.M., and Trudinger, P.A. (eds.), Early Organic Evolution: Implications for Mineral and Energy Resources, Springer-Verlag, Berlin, 336–356.

Claypool, G.E., Holser, W.T., Kaplan, I.R., Sakai, H., and Zak, I., 1980. The age curves of sulfur and oxygen isotopes in marine sulfate and their mutual interpretation. Chemical Geology, 28: 199–260.

Ge, R., Zhu, W., Wilde, S.A., He, J.W., Cui, X., Wang, X., and Zheng, B.H., 2014. Neoproterozoic to Paleozoic long-lived accretionary orogeny in the northern Tarim Craton. Tectonics, 33(3): 302–329.

Guan, S.W., Zhang, C.Y., Ren, R., Zhang, S.C., Wu, L., Ma, P.L., and Han, C.W., 2019. Early Cambrian syndepositional structure of the northern Tarim Basin and a discussion of Cambrian subsalt and deep exploration. Petroleum Exploration and Development, 46(6): 1075–1086.

Hanson, A.D., Zhang, S.C., Moldowan, J.M., Liang, D.G., and Zhang, B.M., 2000. Molecular organic geochemistry of the Tarim basin, northwest China. American Association of Petroleum Geologists Bulletin, 84: 1109–1128.

Horsfield, B., Schenk, H.J., Mills, N., and Welte, D.H., 1992. Closed-system programmed-temperature pyrolysis for simulating the conversion of oil to gas in a deep petroleum reservoir. Organic Geochemistry, 19: 191–204.

Hunt, J.M., 1996. Petroleum Geochemistry and Geology. 2nd Edition. New York: Freeman WH and Co.

Jin, Z.J., Liu, Q.Y., Yun, J.B., and Tenger, W.J., 2017. Potential petroleum sources and exploration directions around the Manjar Sag in the Tarim Basin. Science China Earth Sciences, 60(2): 235–245.

Jin, Z.J., Yun, J.B., and Zhou, B., 2009. Types and characteristics of slope zones in Tarim Basin and their relationship with oil accumulation. Oil & Gas Geology, 30(2): 127–135.

Jin, Z.J., 2011. Formation and accumulation of oil and gas in marine carbonate strata in Chinese sedimentary basins. Science China Earth Sciences, 41(7): 910–926.

Krouse, H.R., Viau, C.A., Eliuk, L.S., Ueda, A., and Halas, S., 1988. Chemical and isotopic evidence of thermochemical sulfate reduction by light hydrocarbon gases in deep carbonate reservoirs. Nature, 333: 415–419.

Li, M.J., Shi, S.B., and Wang, T.G., 2012a. Identification and distribution of chrysene, methylchrysenes and their isomers in crude oils and rock extracts. Organic Geochemistry, 52: 55–66.

Li, S.M., Amrani, A., Pang, X.Q., Yang, H.J., Said-Ahmad, W., Zhang, B.S., and Pang, Q.J., 2015. Origin and quantitative source assessment of deep oils in the Tazhong Uplift, Tarim Basin. Organic Geochemistry, 78: 1–22.

Li, S.M., Pang, X.Q., Zhang, B.S., Xiao, Z.Y., and Gu, Q.Y., 2010. Oil-source rock correlation and quantitative assessment of Ordovician mixed oils in the Tazhong Uplift, Tarim Basin. Petroleum Science, 7: 179–191.

Li, S.M., Shi, Q., Pang, X.Q., Zhang, B.S., and Zhang, H.Z., 2012b. Origin of the unusually high dibenzothiophene oils in Tazhong-4 oilfield of Tarim Basin and its implication in deep petroleum exploration. Organic Geochemistry, 48: 56–80.

Liang, D.G., Zhang, S.C., Zhang, B.M., and Wang, F.Y., 2000. Understanding on marine oil generation in China based on Tarim Basin. Earth Science Frontiers, 7(4): 534–547.

Liu, W.H., Hu, G., Tenger, W. J., Lu, L.F., and Xie, X.M., 2016. Organism assemblages in the Paleozoic source rocks and their implications. Oil & Gas Geology, 37(5): 617–626.

Logan, G.A., Hayes, J.M., Hieshima, G.B., and Summons, R.E., 1995. Terminal Proterozoic reorganization of biogeochemical cycles. Nature, 376: 53–56.

Ma, A.L., Jin, Z.J., Zhang, S.C., and Wang, Y., 2006. Molecular geochemical characteristics of Cambrian-Ordovician source rocks in Tarim Basin, NW China. Geochimica, 35(6): 593–601.

Peters, K.E., Walters, C.C., and Moldowan, J.M., 2005. The Biomarker Guide 2nd edition. New York: Cambridge University Press. 503–504.

Qiu, N.S., Chang, J., Zuo, Y.H., Wang, Y.J., and Li, H.L., 2012. Thermal evolution and Lower Paleozoic source rocks maturation in the Tarim Basin, Northwest China. AAPG Bulletin, 96(5): 789–821.

Song, D.F., Wang, T. G., and Li, M.J., 2016. Geochemistry and possible origin of the hydrocarbons from wells Zhongshen1 and Zhongshen1C, Tazhong uplift. Science China Earth Sciences, 59(4): 840–850.

Sun, Y., Xu, S., Lu, H., and Cuai, P., 2003. Source facies of the Paleozoic petroleum systems in the Tabei Uplift, Tarim Basin, NW China: Implications from aryl isoprenoids in crude oils. Organic Geochemistry, 34: 629–634.

Tissot, B.P., and Welte, D.H., 1984. Petroleum Formation and Occurrence, Second edition. Springer, Berlin, 1–699.

Wang, Z.M., and Xiao, Z.Y., 2004. A comprehensive review concerning the problem of marine crude sources in Tarim Basin. Chinese Science Bulletin, 49: 1–9.

Wang, F.Y., Bian, L.Z., Zhang, S.C., Zhang, B.M., and Liang, D.G., 2001. Two types of hydrocarbon precursor in the Ordovician marine source rocks in the Tarim Basin. Science of China D, 31(2): 96–102.

Wang, F.Y., Du, Z.L., Zhang, B.M., and Zhao, M.J., 2008. Geochemistry of Salgan black shales of Middle-Upper Ordovician in Keping Outcrop, Tarim Basin. Xinjiang Petroleum Geology, 29(6): 687–689.

Yang, H.J., Chen, Y.Q., Tian, J., Du, J.H., and Zhu, Y.F., 2020. Great discovery and its significance for ultra-deep oil and gas exploration in Well Luntan-1 of the Tarim Basin. China Petroleum Exploration, 25(2): 62–72.

Yang, Z.Y., Luo, P., Liu, B., Wang, S., Bai, Y., and Zhou, M., 2017. Analysis of petrological characteristics and origin of siliceous rocks during the earliest Cambrian Yurtus Formation in the Aksu area of the Tarim Basin in Northwest China. Earth Science Frontiers, 24(5): 245–264.

Yu, S., Pan, C.C., Wang, J.J., Jin, X.D., Jiang, L.L., Liu, D.Y., Lu, X.X., Qin, J.Z., Qian, Y.X., Ding, Y., and Chen, H.H., 2011. Correlation of crude oils and oil components from reservoirs and source rocks using carbon isotopic compositions of individual n-alkanes in the Tazhong and Tabei Uplift of the Tarim Basin, China. Organic Geochemistry, 52: 67–80.

Zhang, A.Y., Cai, Y.K., Chu, Z.M., Xu, Y.C., and Shen, P., 1992. Preliminary study on the reversed distribution of stable carbon isotopes in sedimentary organic matter. Acta Sedimentologica Sinica, 10(4): 49–59.

Zhang, S.C., 2000. The migration fractionation: An important mechanism in the formation of condensate and waxy oil. Chinese Science Bulletin, 45: 1341–1344.

Zhang, S.C., Hanson, A.D., Moldowan, J.M., Graham, S.A.,

Liang, D.G., Chang, E., and Fago, F., 2000. Paleozoic oil–source rock correlations in the Tarim Basin, NW China. Organic Geochemistry, 31: 273–286.
Zhang, S.C., and Huang, H.P., 2005. Geochemistry of Palaeozoic marine petroleum from the Tarim Basin, NW China. Part 1.Oil family classification. Organic Geochemistry, 36: 1204–1214.
Zhang, S.C., Huang, H.P., Xiao, Z.Y., and Liang, D.G., 2005. Geochemistry of Palaeozoic marine petroleum from the Tarim Basin, NW China. Part 2. Maturityassessment. Organic Geochemistry, 36: 1215–1225.
Zhang, S.C., Liang, D.G., Li, M.W., Xiao, Z.Y., and He, Z.H., 2002. Molecular fossils and oil–source rock correlations in Tarim Basin, NW China. Chinese Science Bulletin, 47: 20–27.
Zhang, S.C., Liang, D.G., Zhang, B.M., Wang F.Y., Bian, L.Z., and Zhao, M.J., 2004. Generation of marine oil and gas in Tarim Basin. Beijing: Petroleum Industry Press, 1–433.
Zhang, S.C., Gao, Z.Y., Li, J.J., Zhang, B.M., and Gu, Q.Y., 2012. Identification and distribution of marine hydrocarbon source rocks in the Ordovician and Cambrian of the Tarim Basin. Petroleum Exploration and Development, 39(3): 285–294.
Zhang, S.C., Wang, R.L., Jin, Z.J., Zhang, B.M., and Wang, D.R., 2006. The relationship between the Cambrian–Ordovician high-TOC source rock development and paleoenvironmental variations in the Tarim Basin, Western China: Carbon and oxygen isotope evidence. Acta Geologica Sinica, 80(3): 459–466.
Zhang, Y., Wu, G., Wang, J., Li, G., Wan, X., Yang, T., 2020. A new growth model of fault attributes in a strike-slip fault system in the Tarim Basin. Acta Geologica Sinica (English Edition), 94(5): 1373–1380.
Zhao, M.J., and Huang, D.F., 1995. Carbon isotopic distributive characteristics of crude oil monomers produced in different sedimentary environments. Petroleum Geology and Experiment, 17(2): 171–179.
Zhou, Z.Y., and Sheng,G.Y., 1986. Paleogeothermal gradient for the Tarim Basin and oil/gas prospects at great depths. Geochemistry, 5(3): 250–257.
Zhu, C.L., Yan, H., Yun, L., Han,Q., and Ma, H.L., 2014. Characteristics of Cambrian source rocks in well XH1, Shaya uplift, Tarim Basin. Petroleum Geology and Experiment, 36 (5): 626–632.

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