Vol. 92 No. 6 pp. 2297–2309 ACTA GEOLOGICA SINICA (English Edition) Dec. 2018

The Original Organism Assemblages and Kerogen Carbon Isotopic Compositions of the Early Paleozoic Source Rocks in the Tarim Basin, China

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Abstract: Original organisms are the biological precursors of organic matter in source rocks. Original organisms in source rocks are informative for oil-source rock correlation and hydrocarbon potential evaluation, especially for source rocks which have high-over level of thermal maturity. Systematic identification of original organism assemblages of the Lower Paleozoic potential source rocks and detailed carbon isotopic composition of kerogen analyses were conducted for four outcrop sections in the Tarim basin. Results indicated that the original organism assemblages of the lower part of the Lower Cambrian were composed mainly of benthic algae, whereas those of the Upper Cambrian and the Ordovician were characterized by planktonic algae. Kerogen carbon isotopic data demonstrated that the $\delta^{13}C_{kerogen}$ values of source rocks dominated by benthic algae are lower than −34‰, whereas the $\delta^{13}C_{kerogen}$ values of source rocks dominated by planktonic algae are higher than −30‰ in general. We tentatively suggested that the carbon species those are utilized by algae and the carbon isotopic fractionation during photosynthesis are the major controls for the $\delta^{13}C_{kerogen}$ values in the Lower Paleozoic source rocks in the Tarim basin. Correlating the $\delta^{13}C$ values of oils exploited in the Tarim basin, the original organism assemblages, and $\delta^{13}C_{kerogen}$ values of source rocks, it implied that the Lower Paleozoic oils exploited in the Tarim basin should be sourced from the source rocks with original organism assemblages dominated by planktonic algae, and the hydrocarbon sourced from the Cambrian benthic algae should be of great exploration potential in future. Original organism assemblages in source rocks can provide important clues for oil-source rocks correlation, especially for the source rocks with high thermal maturity.

Key words: Tarim basin, the Lower Paleozoic, source rock, original organisms, kerogen carbon isotopes

1 Introduction

Original organisms of organic matters (especially kerogen) refer to formerly living organisms whose organic molecular compounds and part of organ tissues are contributed to kerogen or dispersed organic matters and consequently generate hydrocarbon during thermal alternation. They are the biological precursors of kerogen or dispersed organic matters and may provide new information to the studies of source rocks (Zhang et al., 2004; Bian Lizeng, 2006; Cao et al., 2009; Qin et al., 2015). Generally, the original organisms assemblages of source rock deposited in different sedimentary settings are distinct substantially. Original organisms of marine source rocks are mainly composed of marine algae, seaweeds, and plants, whereas those of terrestrial source rocks mainly consist of plants, fresh algae, and fungi. For the Lower Paleozoic source rocks, the major original organisms are algae and bacteria according to the

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geological record of evolution (Taylor et al., 2009). Previous studies on the hydrocarbon generating stimulation of extant algae demonstrated that algae can be divided into two categories according to their hydrocarbon potential (Wu Qingyou, 1988; Wang Kaifa et al., 1994; Song Yitao and Li Shu, 1995). Interestingly, two categories of algae classified according to hydrocarbon potential correspond well with their life habits. Most algae with high hydrocarbon potential are planktonic algae, whereas algae with low hydrocarbon potential are benthic algae (Liu Wenbin et al., 2005; Qing Jianzhong et al., 2010; Ye Yun et al., 2012). Therefore, the detailed studies on the original organisms of source rocks can shed light on the hydrocarbon potential evaluation, especially for the source rocks with high-over thermal maturity because most geochemical proxies are unavailable, but outer walls of original organism cells could be present and their original morphology could be retained by pyritization under anoxic environments, even their fine micro-structure was observed (Hutton et al., 1980; Stasiuk, 1999; Pancost, 1999).

In theory, the carbon isotopic composition of original organism assemblage has an intrinsic relationship with the carbon isotopic composition of kerogen, and this intrinsic relationship facilitates oil-source rocks correlation. Studies on extant algae have demonstrated that different algae have a different photosynthetic pathway and, consequently, different carbon isotopic compositions (Maberly et al., 1992). These original organisms with different carbon isotopic compositions are the major biological precursors for the formation of kerogen via the so-called depolymerization recondensation pathway (Durand, 1980; Tissot and Welte, 1984) or an alternatives selective preservation way (Tegelaar et al., 1989). In the depolymerization recondensation process, part of naturally occurring macromolecular substances (e.g. polysaccharides and proteins) and low-molecular-weight lipids of original organisms are condensed together to form kerogen. Whereas in the selective preservation, specific organic substances, especially out walls of cells, are selectively preserved during the processes of sedimentation and diagenesis. Some organs of original organisms are thought to survive selectively and may become quantitatively important in kerogens (Tegelaar et al., 1989; Taylor et al., 1998). Therefore, whatever process, original organisms have significant impactions on the carbon isotopic composition of kerogen. Source rocks containing different original organism assemblages should have different kerogen carbon isotopic compositions. In addition, previous research indicated that the carbon isotopic fractionation of between the whole hydrocarbon and kerogen should not exceed 2‰–3‰ due to the limited organic carbon that can be converted into hydrocarbons (Tissot and Welte, 1984). Thus, the original organisms and the carbon isotopic composition of kerogen can provide insight into oil-source rocks correlation. As so far, original organism assemblages and the carbon isotopic composition of kerogen with high thermal maturity (especially for the Lower Paleozoic source rocks) have not been studied in detail.

The Lower Paleozoic in the Tarim Basin is important petroliferous in China (Sun Dongsheng et al., 2017). Exploration suggests that the major source rocks in the platform-basin transitional area generally include the Cambrian and Ordovician (Jia Chengzao, 1997; Zhang et al., 2000; Jia Wanglu and Peng Pingan, 2004; Zhang Shuichang et al., 2004; Xiao Zhongyao et al., 2005; Cai et al., 2015). But they were buried deeply and show high maturity, and most of them have not been drilled. Knowledge of the Lower Paleozoic source rocks and petroleum in the Tarim Basin are still controversial (Sun et al., 2003; Ma Anlai et al., 2006; Liu et al., 2011; Liu Quanyou, 2013; Li et al., 2015; Li Chunquan and Chen Honghan, 2015; Wang Bin et al., 2015; Pang et al., 2016; Xiao et al., 2016).

In this study, four Lower Paleozoic outcrop sections in the Kuruketage and Keping areas in the margin of the Tarim basin were selected (Fig. 1), and the original organisms of source rocks and kerogen carbon isotopes were analyzed. We aim to 1) uncover the intrinsic correlation between original organisms of source rocks and the kerogen carbon isotopic composition, and 2) carry out a case study for the oil-source correlation based on original organisms and $\delta^{13}C_{kerogen}$ of source rocks. The results should not only shed light on the source rock evaluation and oil-source correlation in the Tarim Basin but also have important significance for the petroleum exploration in the Paleozoic marine carbonate sequences throughout China, even in the world.

2 Geological Settings

The Kuruketag and Keping regions selected in this study were in the northern passive continental margin of the Tarim plate (Fig. 1). During the Cambrian and Ordovician periods, the potential source rocks, including the Xishanbulak, Xidashan, Moheershan, Heituao, Yuurtusi, Saergan, and Yingan Formations, were deposited in both the Kuruktag and Keping regions and cropped out well in these regions (Jiang Haijian et al., 2017; Yang Xin et al., 2017) (Fig. 1).

The Kuruktag region is located at the east side of northern Tarim Basin, bounded by the Kongquehe and Xingeer faults to the south and north, and the E-W

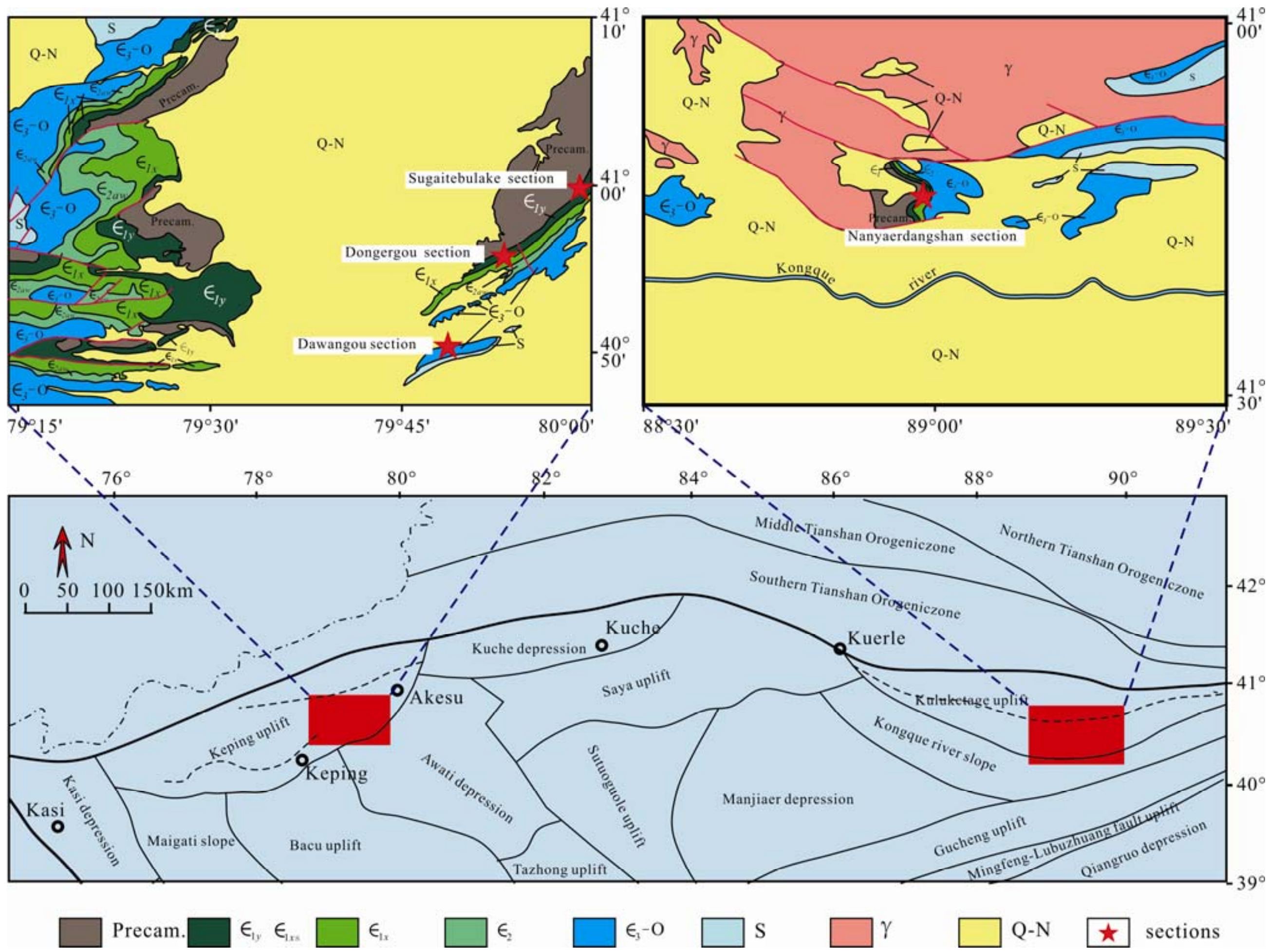

Fig. 1. Location of outcrop sections and geological sketch map for studying area.

trending Xingdi fault runs across the Kuruketag region (The second geological brigade of the Xinjiang Uygur Autonomous Region Bureau of Geology, 1996; The third geological brigade of the Xinjiang Bureau of Geology, 2006). During the Paleozoic, the southern Kuruktag was a semi-deep basin, whereas the northern Kuruktag was a shallow-water platform (Jia Chengzhao, 1997). In the Kuruketag, the Cambrian and Ordovician consist of the Xishanbulak ($\epsilon_1 xs$), Xidashan ($\epsilon_1 xd$), Moheershan ($\epsilon_2 m$), Tuurshaketag (ϵ_3-$O_1 t$), and Heituao ($O_{1\text{-}2} h$) Formations. The Xishanbulak Formation ($\epsilon_1 xs$) mainly consists of pyroclastic rocks, siliceous rocks, and black mudstones. The Xidashan Formation ($\epsilon_1 xd$) was dominated by siliceous mudstone and micritic dolomite. The Moheershan Formation ($\epsilon_2 m$) is mainly composed of micritic limestone and mudstone. The Tuershaketag Formation (ϵ_3-$O_1 t$) mainly consists of micritic limestone, nodular limestone, and siltstone. The Heituao Formation ($O_{1\text{-}2} h$) mainly consists of black mudstone, muddy siltstone, and interlayered with calcareous sandstone.

The Keping region is located on the west side of the northern Tarim Basin, separated from the Bachu uplift and Awati Depression by the Keping and Shajingzi faults, bounded by the Aheqi fault to the north, and adjacent to the Kuche Depression and the Kelayurgun fault to the east (Fig. 1) (Lu Huafu et al., 1998). The Cambrian and Ordovician in Keping region include the Yuurtusi, Sharebulak, Wusongger, Shayilike, Avatag, Qiulitage, and Saergan Formations. Among them, the lower part of the Yuertusi Formation mainly consists of greyish black carbonaceous shales, siliceous rocks, and phosphate, whereas the upper part of the Yuertusi Formation is mainly composed of dolomitic limestone. The lower part of the Sharebulak Formation consists of black and greyish black marlstone interbedded with carbonaceous shales, and the upper part of the Shaerbulak Formation is dominated by grey dolomitic limestone. The Wusongger Formation is comprised of yellowish limestone, dolomitic limestone, dolomite, calcareous sandstone, and siltstone. The lower part of the Shayilike Formation is dolomitic limestone with cherts, and the upper part of the Shayilike Formation consists of red gypsiferous marlstone, siltstone, and marlstone. The Avatage Formation includes yellow limestone interbedded with greyish brown chert containing dolomitic limestone. The Qiulitage Formation displays a set of dolomite and limestone. The Saargan Formation shows a set of black carbonaceous shale interbedded with laminated limestone with graptolite.

3 Samples and Methods

The Paleozoic potential source rocks in the four outcrop sections (i.e., the Nanyaerdangshan, Sugaitebulark, Dongergou, and Dawangou sections) in the Kuruketag and Keping regions in the northern Tarim Basin were investigated for studying original organism and kerogen carbon isotopes. 66 fresh black shales, mudstones, and marlstones samples were collected, and the locations of the sections and samples are shown in Fig. 1 and Table 1, respectively.

The identification of the original organism in source rocks is similar to traditional organic petrologic studies. In thin sections, the microscopic characteristics and morphology of the biological tissues and thallus were studied under transmitted and reflected light using a Leica DM2500P microscope.

The samples for kerogen carbon isotopic analyses were ground into approximately 1 cm^3. Fresh fragments were picked out, soaked for 24 hours in 3 mol HCl acid and washed 3–4 times with distilled water, and then crushed and sieved (<110 mesh). The powder was soaked in 50% HCl (v/v) for 24 hours. The remains reacted with 15% HF for 24 hours and rinsed 3–4 times with distilled water. The dried powders were used for carbon isotopic analyses by MAT-252. The $\delta^{13}C$ is calculated as follows: $\delta^{13}C = \{[(^{13}C/^{12}C)_{\text{Sample}} - (^{13}C/^{12}C)_{\text{Standard sample}}] / (^{13}C/^{12}C)_{\text{Standard sample}}\} \times 1000$. The analysis accuracy is ±0. 02‰, and the data error is ±0.1‰.

All the analyses were completed at the Wuxi Institute of Petroleum Geology, SINOPEC Exploration, and Production Research Institute.

4 Results

4.1 General characteristics of original organisms in the Lower Paleozoic source rocks

As mentioned above, the major original organisms of source rocks in the Lower Paleozoic source rocks are algae. Algae can be grouped into planktonic and benthic algae based on their life habits and their hydrocarbon potential (Wu Qinyou, 1987; Wang Kaifa et al., 1994; Song Yitao and Li Shu, 1995; Liu Wenbin et al., 2005; Qin et al., 2010). Generally, most planktonic algae and biomass exhibit spherical shape and aggregation of spherical algae, but few have single filament appearance. Most amorphous appearance are usually considered planktonic biomass-derived (Lewan, 1986). Typical planktonic algae represented by *Cyanobacteria*, *Chlorophyta Prasinophyceae*, *Chlorophyceae Volvocales*, *Tetrasporales*, *Botryococcus*, *Chlorellales*, *Dinophyta Dinophyceae*, and *Heterokontophyta Pinguiophyceae* are spherical, aggregate shapes (Fott, 1971; Lee, 2008). On the other hand, most benthic algae including *Rhodophyta Rhodophyceae*, *Chlorophyta Ulvophyceae*, and *Heterokontophyta Phaeophyceae* have a plate-like thallus and filament aggregation thallus, which are significantly different from planktonic algae in shape (Fott, 1971; Lee, 2008). In addition, most benthic algae have particular reproductive organs and cell structure, for example, *Rhodophyta* have spherical or zonal tri-sporangia or tetra-sporangia, and *Phaeophyceae* have single-chamber or multi-chamber sporangia (Fott, 1971; Lee, 2008).

Based on the morphological features of the thallus, reproductive organs, and cell structure, 66 fresh samples were studied in detail under an optical microscope. Results indicated that the Lower Paleozoic source rocks in the Tarim had a variety of original organisms, and were mainly benthic and planktonic algae. In general, the benthic algae were composed of macro *Rhodophytaeand Rhodophytae sporangia* (Fig. 2a and b) and *Phaeophyceae* (Fig. 2c), and planktonic algae consisted mainly of *Cyanobacteria*, spherical *Dinoflagellate*aggregation (Fig. 2d), *Paradesmocapsa Zhenii* (Fig. 2e), smooth *Chlorella* (Fig. 2f), *Chlorella pyrenoidosa* (Fig. 2g), *Volvox*, etc. (Fig. 2h).

The thallus of the Early Paleozoic benthic algae in the Tarim basin is often plate-like with a certain thickness, and has a clearly visible external perithallus and internal hypothallus (Fig. 3a). As shown in Figure 3, hypothallus cells presented mesh alignment, whereas the perithallus

Table 1 Sections, Formations and samples

Study area	Section	Formation	Distribution of samples
Kuluketage	Nanyaerdangshan section	Xishanbulake, Xidanshan, Mohershan, Tuersaketage, and Heituao Formations	4 samples for Xishanbulake Formation 8 samples for Xidashan Formation 4 samples for Mohershan Formation 3 samples for Tuersaketage Formation 3 samples for Heituao Formation
Keping	Sugaitebulake section	Yuertusi and Xiaoerbulake Formations	11 samples forYuertusi Formation 3 samples for Xiaoerbulake Formation
	Dongergou section	Yuertusi Formation	9 samples for Yuertusi Formation
	Dawanggou section	Saergan Formation	21 samples for Saergan Formation

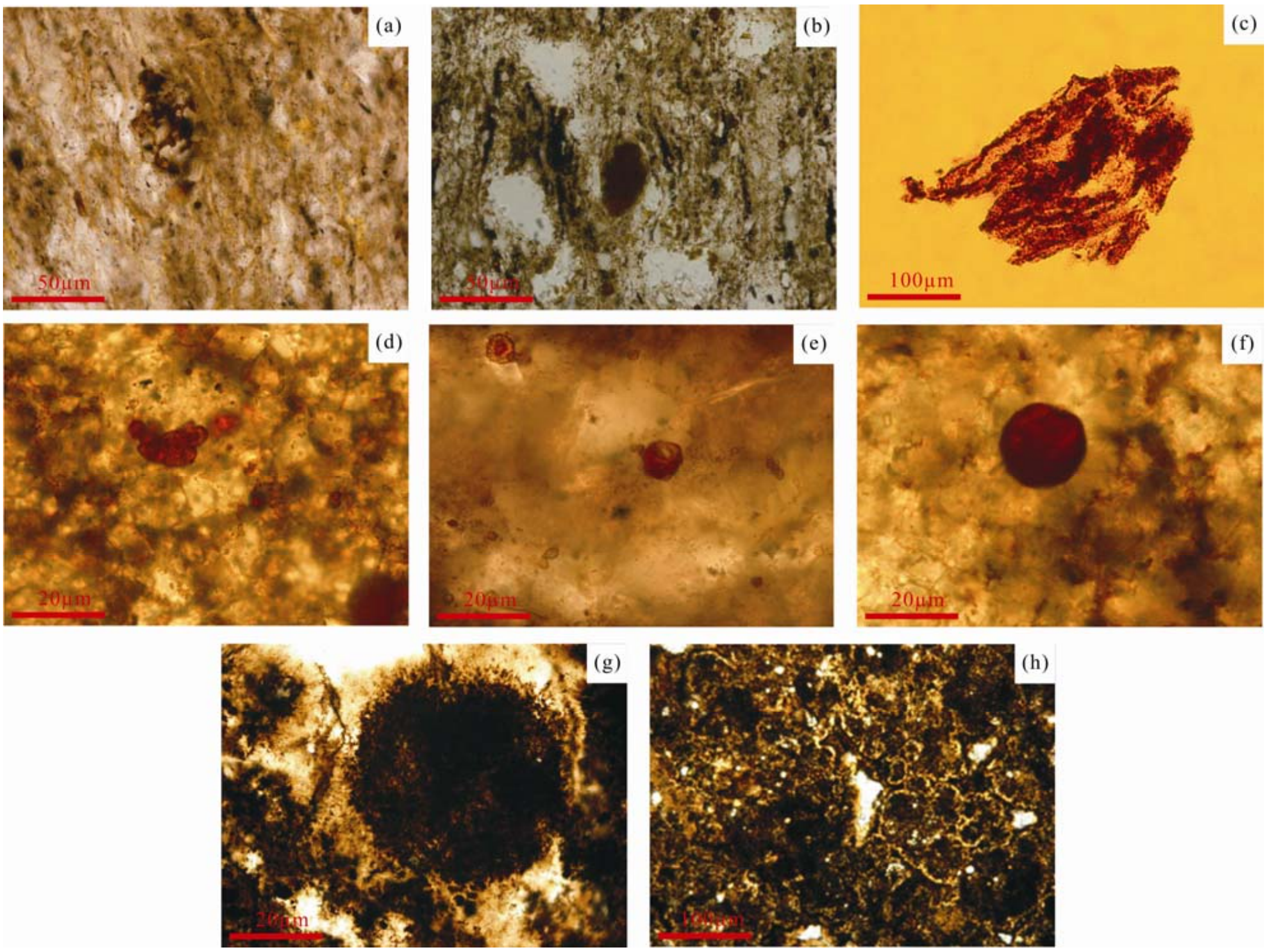

Fig. 2. Typical original organisms in the northern Tarim Basin.

was densely packed with chlorophyll cells. In the reproductive organ of *Rhodophyta*, the sporangium developed inside the *Rhodophyta* thallus, which was another important clue for the identification of benthic algae. When the internal spores were discharged, crypts formed in the thallus (Fig. 3a). Figure 3b is a magnification of the *Rhodophyta* sporangium in which the spores are clear.

Planktonic algae in the Lower Paleozoic source rocks in the Tarim basin are spherical under the microscope, and significantly different from the benthic algae (Figs. 3c–d). Depending on the sizes and morphological features, the Early Paleozoic planktonic algae in the Tarim basin can be divided into two groups (i.e., ultramicro-planktonic and micro-planktonic algae). Most ultramicro-planktonic algae are single cells with a small size and are mainly composed of micro-spherulitic cyanobacteria, such as *Synechococcus*, *Synechocystis*, and *Prochlorococcus*. Most planktonic algae in the Lower Paleozoic in the Tarim basin are slightly larger than 2 μm and range up to approximately 5 μm (Fig. 3c). Because of their small size, larger surface area, and higher nutrient diffusive gradients in the cells, they grow well in the oligotrophic sea, where the micro-phytoplankton rarely occurs (Willian et al., 2009).

Micro-planktonic algae are also an important part of the Early Paleozoic planktonic algae. Their cells contain gas vesicles and usually gather on the water surface leading to algal blooms, which flow with the wind and waves, such as with *Aphanizomenon*, *Volvox*, *Anabaena*, etc. Their aggregations are generally oblong and spherically shaped (Fig. 3d), and they often occur at the shore, especially in static waters, such as in bays and lagoons.

4.2 Original organism assemblages of the Lower Paleozoic potential source rocks in the Tarim

4.2.1 Original organism assemblages in the Nanyardangshan section in Kuruktag

In the Nanyardangshan section in Kuluketaga area, the potential source rocks were developed in the Xishanbulak, Xidashan, Morhershan, Turshaketage, and Heituao Formations in ascender order. A total of 22 fresh samples were examined by transmitted and reflected light. In general, the original organisms of the Lower Cambrian Xishanbulak Formation include benthic *Rhodophytae*, *Phaeophyceae*, *Isophyllum*, and planktonic

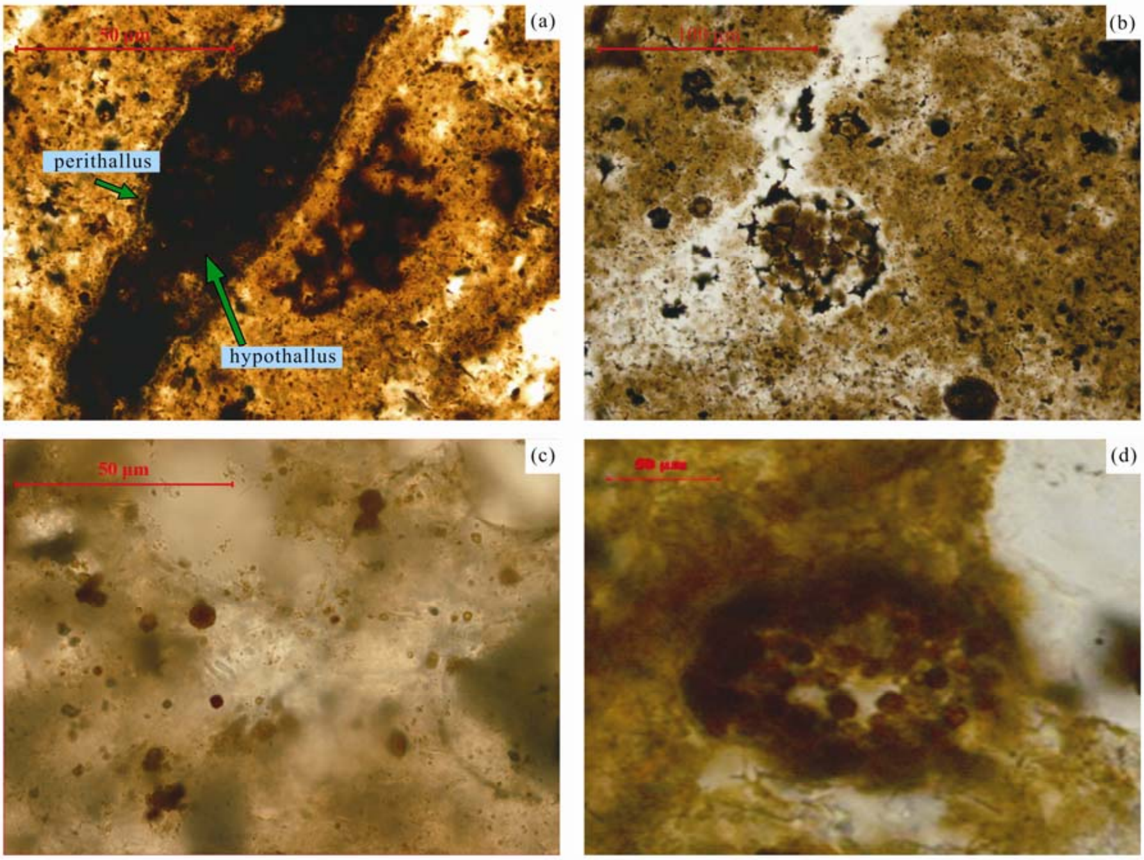

Fig. 3. Identification features of original organisms in the northern Tarim Basin.

Paradesmocapsa Zhenii, etc. In the Xishanbulak Formation, the original organisms gradually change upward to planktonic algae. In the top of the Formation, the original organism assemblage was mainly composed of planktonic *Cyanobacteria* and *Paradesmocapsa Zhenii*. The spherical *Dinoflagellate* content generally gradually increasing upward from the middle of the Formation, whereas the benthic assemblages, such as those of *Rhodophytae*, *Phaeophyceae*, and *Isophyllum*,were only dominant in the lowest part of the Xishanbulak Formation.

In the Xidashan Formation, the original organisms were mainly planktonic algae with a small amount of benthic algae fragments. Compared to the Xishanbulak Formation, the planktonic algae (*Paleogloeodinium*, unicellular and tetra-cellular *Chlorophyta*, and *Acritarchs*) exhibited a clear spherical structure under microscopic examination.

The original organism assemblages in the Middle Cambrian Mohershan Formation were similar to those in the Xidashan Formation and were also primarily composed of planktonic algae, including spherical *Dinoflagellate*, unicellular *Chlorophyta*, and *Acritarchs*, with a small number of benthic algae. However, the fragments of *Nematothallus* began to appear in the upper part of the Mohershan Formation, which may indicate that the water depth began to decrease (Bian Lizeng, 2006).

The original organism assemblages in the Upper Cambrian to Lower Ordovician Turshaketage Formation were similar to those of the Moheer Mountain Formation, which is also mainly composed of planktonic spherical *Dinoflagellate*, unicellular *Chlorophyta* as well as *Acritarchs*. The difference is that the *Nematothallus* and benthic algae contents are higher.

In the Lower-Middle Ordovician Heituao Formation, the original organism assemblages show significant differences; graptolite and pyrite have developed, the benthic *Rhodophytae* content has increased, and the planktonic algae content has decreased.

4.2.2 Original organism assemblages in the Sugatebulak section

The examination of original organism on 14 samples from the Lower Cambrian Yuurtusi Formation in the Sugatebulak section indicated that the major original organisms included benthic algae fragments, planktonic algae (smooth *Chlorella*, *Micrhystridium*, spherical *Dinoflagellate*, and *Volvox*), and laminar cyanobacteria mats. In addition, some animal fragments (i.e., a large number of sponge spicules) were observed in the sample TAS-4.

Similar to the Xishanbulak Formation in the

Nanyardangshan section, the original organism assemblages of the lower part of the Yuurtusi Formation in this section were comprised of benthic and planktonic algae. However, starting from the sample TAS-8, the content of benthic algae fragments decreased, whereas planktonic algae content increased significantly, specifically planktonic spherical *Dinoflagellate* and *Volvox*. At the top of the Yuurtusi Formation, original organisms were dominated by cyanobacteria.

4.2.3 Original organism assemblages in the Dongergou section in Akesu

In this section, the Original organism assemblages of the Yuurtusi Formation are mainly benthic algae. A large amount of benthic *Rhodophyta* fragments and *Rhodophyta* cystocarp were observed, whereas *Chlorophyta*, *Volvox*, *Micrhystridium*, spherical *Dinoflagellate*, and other planktonic algae were only observed in the samples (TDE-8). The original organism assemblages of the Dongergou section were distinctly different from the Yuurtusi and Xishanbulak Formations in the Sugaitebulak section, in which the original organisms were composed of benthic and planktonic algae.

4.2.4 Original organism assemblages in the Dawangou section in Keping

Overall, 21 samples were collected in this section for original organism identification. Compared to the Ordovician Heituao Formation in the Nanyardangshan section, original organisms of the Saargan Formation were mainly composed of *Cyanobacteria* and *Chlorella*. The lithologic facies of the Saargan Formation are also different from those of the Heituao Formation in the Nanyardangshan section and were dominated by black shales interbedded with marlstones.

4.3 Carbon isotopes of kerogen of the Lower Paleozoic source rocks

A total of 66 samples were analyzed for carbon isotopes of kerogen. The results are shown in Table 2. They varied from −38‰ to −25‰. Based on the correlation between $\delta^{13}C_{kerogen}$ and original organism assemblages in the four sections, it was clear that the $\delta^{13}C_{kerogen}$ was less than −34‰ for source rocks with benthic algae, whereas the $\delta^{13}C_{kerogen}$ of hydrocarbon source rocks dominated by planktonic algae was generally greater than −30‰ (Fig. 4; Table 2).

In the Nanyardangshan section in the Kuruktag region, the original organisms of Sample TNY-3 from the lower part of the Xishanbulake Formation were composed of benthic algae, and the $\delta^{13}C_{kerogen}$ had a minimum value of −34.2‰. In the Xidashan and Moheershan Formations, the original organism assemblages were mainly composed of planktonic algae, and the average value of $\delta^{13}C_{kerogen}$ was −30.2‰. In the Heituao and the Tuurshaketag Formations, the original organism assemblages were dominated by planktonic algae, and the average value of $\delta^{13}C_{kerogen}$ predictably increased to −27.9‰ (Fig. 4; Table 2).

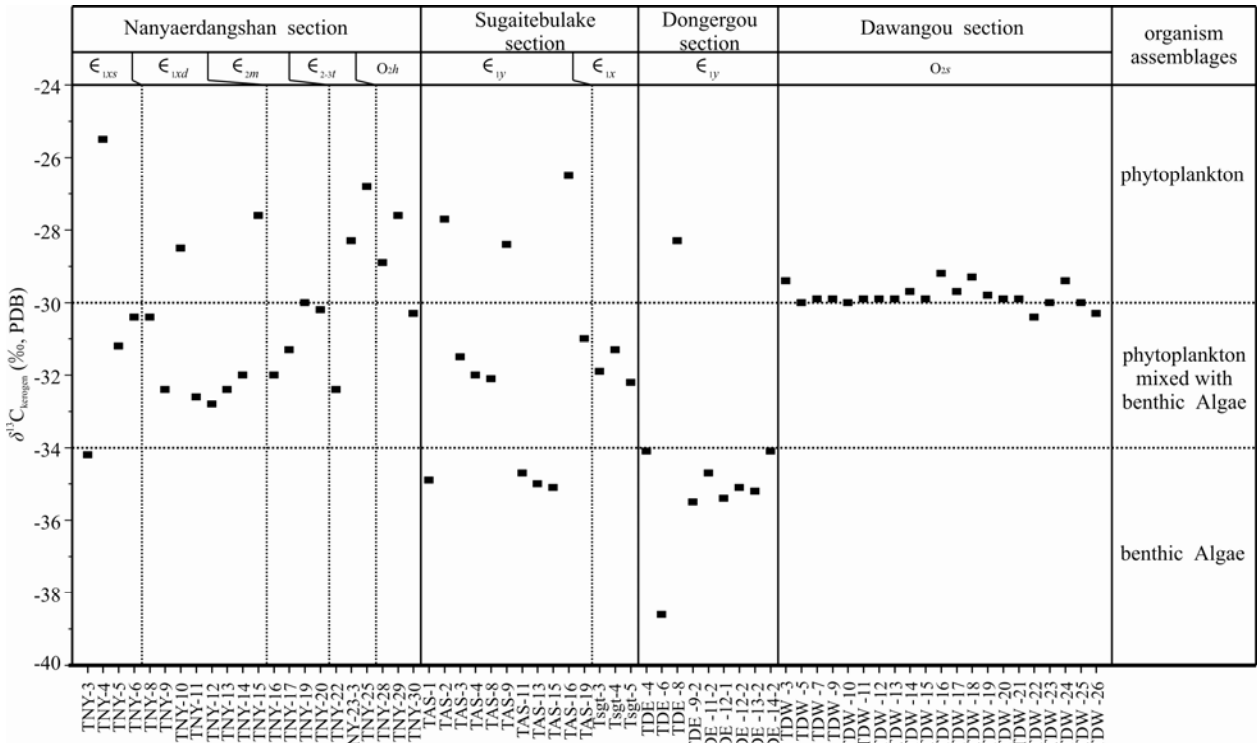

Fig. 4. The carbon isotopic composition of kerogen and original organisms.

Table 2 The carbon isotopes of kerogen and original organism assemblages

Sections	Samples	Formations	lithology	$\delta^{13}C_{kerogen}$ (‰, PDB)	Organism assemblages
The Nanyaerdangshan section	TNY−3	Є$_1xs$	Silicalite	−34.2	Benthic algae
	TNY−4	Є$_1xs$	Black shale	−25.5	Planktonic algae
	TNY−5	Є$_1xs$	Black shale	−31.2	Benthic and Planktonic algae
	TNY−6	Є$_1xs$	Black shale	−30.4	Benthic and Planktonic algae
	TNY−8	Є$_1xd$	Black shale	−30.4	Benthic and Planktonic algae
	TNY−9	Є$_1xd$	Black shale	−32.4	Benthic and Planktonic algae
	TNY−10	Є$_1xd$	Black marlstone	−28.5	Benthic and Planktonic algae
	TNY−11	Є$_1xd$	Black shale	−32.6	Benthic and Planktonic algae
	TNY−12	Є$_1xd$	Black shale	−32.8	Benthic and Planktonic algae
	TNY−13	Є$_1xd$	Black shale	−32.4	Benthic and Planktonic algae
	TNY−14	Є$_1xd$	Black shale	−32.0	Benthic and Planktonic algae
	TNY−15	Є$_1xd$	Silty shale	−27.6	Benthic and Planktonic algae
	TNY−16	Є$_2m$	Black shale	−32.0	Benthic and Planktonic algae
	TNY−17	Є$_2m$	Silty shale	−31.3	Benthic and Planktonic algae
	TNY−19	Є$_2m$	Silty shale	−30.0	Benthic and Planktonic algae
	TNY−20	Є$_2m$	Silty shale	−30.2	Benthic and Planktonic algae
	TNY−22	Є$_3$−O_1tr	Dolomite	−32.4	Benthic and Planktonic algae
	TNY−23−3	Є$_3$−O_1tr	Greyish−green shale	−28.3	Planktonic algae
	TNY−25	Є$_3$−O_1tr	Greyish−green shale	−26.8	Planktonic algae
	TNY−28	$O_{1-2}h$	Greyish−green shale	−28.9	Planktonic algae
	TNY−29	$O_{1-2}h$	Greyish−green shale	−27.6	Planktonic algae
	TNY−30	$O_{1-2}h$	Greyish−green shale	−30.3	Planktonic and Benthic algae
The Sugaitebulake section	TAS−1	Є$_1y$	Silicalite	−34.9	Benthic algae
	TAS−2	Є$_1y$	Silicalite	−27.7	Planktonic algae
	TAS−3	Є$_1y$	Black shale	−31.5	Benthic and Planktonic algae
	TAS−4	Є$_1y$	Silicalite	−32	Benthic and Planktonic algae
	TAS−8	Є$_1y$	Black shale	−32.1	Benthic and Planktonic algae
	TAS−9	Є$_1y$	Greyish mudstone	−28.4	Planktonic algae
	TAS−11	Є$_1y$	Black shale	−34.7	Benthic algae
	TAS−13	Є$_1y$	Black shale	−35.0	Benthic algae
	TAS−15	Є$_1y$	Black shale	−35.1	Benthic algae
	TAS−16	Є$_1y$	Black shale	−26.5	Planktonic algae
	TAS−19	Є$_1y$	Greyish mudstone	−31.0	Planktonic and Benthic algae
	Tsgt−3	Є$_1x$	Argillaceous limestone	−31.9	Planktonic and Benthic algae
	Tsgt−4	Є$_1x$	Argillaceous limestone	−31.3	Planktonic and Benthic algae
	Tsgt−5	Є$_1x$	Argillaceous limestone	−32.2	Planktonic and Benthic algae
The Dongergou section	TDE −4	Є$_1y$	Black shale	−34.1	Benthic algae
	TDE −6	Є$_1y$	Black shale	−38.6	Benthic algae
	TDE −8	Є$_1y$	Black shale	−28.3	Phytoplankton
	TDE −9−2	Є$_1y$	Black shale	−35.5	Benthic algae
	TDE −11−2	Є$_1y$	Black shale	−34.7	Benthic algae
	TDE −12−1	Є$_1y$	Silicalite	−35.4	Benthic algae
	TDE −12−2	Є$_1y$	Black shale	−35.1	Benthic algae
	TDE −13−2	Є$_1y$	Black shale	−35.2	Benthic algae
	TDE −14−2	Є$_1y$	Black shale	−34.1	Benthic algae
The Dawangou section	TDW −3	$O_{2-3}s$	Black shale	−29.4	Planktonic + less benthic algae
	TDW −5	$O_{2-3}s$	Black shale	−30.0	Planktonic + less benthic algae
	TDW −7	$O_{2-3}s$	Black shale	−29.9	Planktonic + less benthic algae
	TDW −9	$O_{2-3}s$	Black shale	−29.9	Planktonic + less benthic algae
	TDW −10	$O_{2-3}s$	Argillaceous limestone	−30.0	Planktonic + less benthic algae
	TDW −11	$O_{2-3}s$	Black shale	−29.9	Planktonic + less benthic algae
	TDW −12	$O_{2-3}s$	Argillaceous limestone	−29.9	Planktonic + less benthic algae
	TDW −13	$O_{2-3}s$	Black shale	−29.9	Planktonic + less benthic algae
	TDW −14	$O_{2-3}s$	Argillaceous limestone	−29.7	Planktonic + less benthic algae
	TDW −15	$O_{2-3}s$	Black shale	−29.9	Planktonic + less benthic algae
	TDW −16	$O_{2-3}s$	Argillaceous limestone	−29.2	Planktonic + less benthic algae
	TDW −17	$O_{2-3}s$	Black shale	−29.7	Planktonic + less benthic algae
	TDW −18	$O_{2-3}s$	Argillaceous limestone	−29.3	Planktonic + less benthic algae
	TDW −19	$O_{2-3}s$	Black shale	−29.8	Planktonic + less benthic algae
	TDW −20	$O_{2-3}s$	Argillaceous limestone	−29.9	Planktonic + less benthic algae
	TDW −21	$O_{2-3}s$	Black shale	−29.9	Planktonic + less benthic algae
	TDW −22	$O_{2-3}s$	Argillaceous limestone	−30.4	Planktonic + less benthic algae
	TDW −23	$O_{2-3}s$	Black shale	−30	Planktonic + less benthic algae
	TDW −24	$O_{2-3}s$	Argillaceous limestone	−29.4	Planktonic + less benthic algae
	TDW −25	$O_{2-3}s$	Black shale	−30.0	Planktonic + less benthic algae
	TDW −26	$O_{2-3}s$	Argillaceous limestone	−30.3	Planktonic + less benthic algae

In the Keping region on the northwestern edge of the Tarim Basin, similar results that the source rocks with benthic algae have low $\delta^{13}C_{kerogen}$ values and those with planktonic algae have high $\delta^{13}C_{kerogen}$ values were obtained. For example, in the Yuurtusi Formation in the Sugatebulak section, the $\delta^{13}C_{kerogen}$ of samples TAS-1, TAS-11, TAS-13, and TAS-15 dominated by benthic algae ranged from −35.1‰ to −34.7‰, whereas the $\delta^{13}C_{kerogen}$ of samples TAS-2, TAS-9, and TAS-16 dominated by planktonic algae ranged from −28.5‰ to −26.5‰. In the Dongergou section in the Keping region where the original organisms of the Yuurtusi Formation were mainly composed of benthic algae (except for sample TDE-8), the $\delta^{13}C_{kerogen}$ were generally low, ranging from −38.6‰ to −34.1‰. As for the Ordovician Saargan Formation in the Dawangou section, the original organisms were mainly composed of Cyanobacteria, *Micrhystridium*, and other planktonic algae. The range of $\delta^{13}C_{kerogen}$ values was narrow, mostly within the range from −30.4‰ to −29.7‰ (Fig. 4; Table 2).

In summary, the $\delta^{13}C_{kerogen}$ of source rocks with benthic algae are lower than −34‰, whereas the $\delta^{13}C_{kerogen}$ of hydrocarbon source rocks dominated by planktonic algae are generally higher than −30‰ in the northern Tarim Basin. This conclusion is confirmed by the Ordovician Decorah Formation source rocks. Research of Pancost et al. (1999) indicated that the Ordovician Decorah Formation source rocks dominated by planktonic *Gloeocapsomorpha prisca* have $\delta^{13}C_{kerogen}$ in the range of −30‰ to −23‰ (Pancost et al., 1999).

5 Discussion

5.1 How did original organisms influence $\delta^{13}C_{kerogen}$ of source rocks?

Although there are many factors that control the carbon isotopic composition of kerogen such as sedimentary environments, thermal diagenesis, and hydrocarbon generation processes. In fact, sedimentary settings control the development of algae (Hu Guang, 2014), and the carbon isotopic fractionation should not exceed 2‰–3‰ during hydrocarbon generation processes (Tissot and Welte, 1984). Thus, the carbon isotopic composition of original organism assemblages in source rocks might be mainly responsible for $\delta^{13}C_{kerogen}$ because the major ingredients of kerogen are derived from original organisms (Durand, 1980; Tissot and Welte, 1984; Tegelaar et al., 1989). This study also presents clearly that source rocks with different original organism assemblages have different $\delta^{13}C_{kerogen}$. The result that the $\delta^{13}C_{kerogen}$ of source rocks with benthic algae is generally lower than that of source rocks with planktonic algae seems to imply that the $\delta^{13}C_{kerogen}$ of source rocks were related to the original organism assemblages. How did original organism assemblages influence $\delta^{13}C_{kerogen}$? Carbon isotopic composition of extant algae may provide useful clues to decipher the variation of $\delta^{13}C_{kerogen}$ of the Lower Paleozoic source rocks with different original organism assemblages in the Tarim.

Recent studies on carbon isotopic composition of extant benthic algae and planktonic algae have also demonstrated that the carbon isotopic composition of planktonic algae is heavier than that of benthic algae (Fry et al., 1982; Fenton and Ritz, 1989). Carbon isotopic composition of cultured extant algae suggested that the $\delta^{13}C$ values of most benthic algae grown in the sub-tidal zone were lower than −30‰, with a mean value of −33.5‰ (Wiencke and Fischer, 1990; Ye et al., 1991), whereas the $\delta^{13}C$ values of planktonic algae were greater than −30‰, generally ranging from −23.5‰ to −12.3‰ (Brutemark et al., 2009). Recently, researchers believed that the higher growth rate and yield of planktonic algae could result in a lesser extent of carbon isotope fractionation (Laws et al., 1995).

In addition, the $\delta^{13}C$ of sea water of the Cambrian and Ordovician might affect the $\delta^{13}C_{kerogen}$. It was believed that the $\delta^{13}C$ of marine carbonate became gradually higher from ~ −4‰ to ~ −2‰ from the Cambrian to the Ordovician (Buggisch et al., 2003; Maloof et al., 2005; Saltzman, 2005; Saltzman and Yong, 2005; Dilliard et al., 2007; Bergstrom et al., 2010). However, the kerogen carbon isotope in this study did not show a significant heavier trend from the Cambrian to Ordovician (Fig. 4). Thus, the species of algae might be mainly responsible for the kerogen carbon isotopic composition of the Paleozoic source rocks in the Tarim basin. Generally, there are two independent factors that affect the algal carbon isotopic composition and consequently affect the $\delta^{13}C_{kerogen}$ of source rocks: 1) carbon sources utilized by algae; 2) carbon isotope fractionation during photosynthesis.

The species of carbon available for algae photosynthesis include atmospheric CO_2, dissolved atmospheric CO_2, and HCO_3^- in water, as well as CO_2 and HCO_3^- released from the decomposing organisms at the water-sediment interface. Among them, atmospheric CO_2 has a heavier carbon isotopic composition, in which the $\delta^{13}C$ was approximate −6.5‰ before the industrial revolution. The $\delta^{13}C$ value of the dissolved atmospheric CO_2 and HCO_3^- in water ranges from 0‰ to 2‰, whereas CO_2 and HCO_3^- released from the decomposing organisms at the water-sediment interface have a $\delta^{13}C$ value ranging from −30‰ to −20‰ (Dunkley-Jones et al., 2010). If the carbon isotopic fractionation during the physiological metabolism processions between benthic and planktonic algae is negligible, then the carbon isotopic composition of different carbon species utilized by algae will play a key role in the $\delta^{13}C_{kerogen}$ of source rocks with different organism assemblages.

For benthic algae, the dissolved CO_2 and HCO_3^- from the decomposition of organisms at the sediment-water interface are important available carbon sources. These carbon species are characterized by low $\delta^{13}C$ values. Thus, the $\delta^{13}C_{kerogen}$ of source rocks dominated by benthic algae will be low. In contrast to benthic algae, planktonic algae, mainly float on the surface or in the upper part of the euphotic zone, utilize atmospheric CO_2 and HCO_3^- which have heavier carbon isotopic composition, and consequently lead to the higher $\delta^{13}C_{kerogen}$ values of source rocks dominated by planktonic algae.

In addition, Raven et al. (2002) built a formula to calculate the carbon isotope composition for algae: $(1+\delta^{13}C_{source})/\ (1+\delta^{13}C_{algae})=\ (\alpha_d\times(C_o-C_i)/Co)+\ (\alpha_c\times C_i/C_o)$, where C_i refers to the carbon dioxide content in the intracellular gas chamber, Co is the carbon dioxide content in carbon pools, α_d is the carbon isotope fractionation factor of carboxylase (≈1.027), and Ci refers to the diffusion coefficient of carbon dioxide entering the cell from the carbon pool (≈1.0044) (Maberly et al., 1992; Raven et al., 2002). Given the $\delta^{13}C$ value of HCO_3^- of the surface seawater is approximately 0‰ and dissolved atmospheric CO_2 and HCO_3^- in the euphotic zone were the main carbon species utilized by planktonic algae, the $\delta^{13}C$ value of algae calculated according to the formula may not be higher than −30‰. This calculated $\delta^{13}C$ value is consistent with our observation that the $\delta^{13}C_{kerogen}$ of source rocks dominated mainly by planktonic algae are generally less than −30‰. However, in the Tarim Basin, the Lower Paleozoic source rocks with benthic algae were deposited on a shelf that was under the wave base (Hu Guang, 2014). These benthic algae had less opportunity to consume atmospheric CO_2 and HCO_3^- in the euphotic zone. Therefore, the $\delta^{13}C_{kerogen}$ of source rock with benthic algae is generally lower than −34‰.

Another important factor that affects the carbon isotope composition of algae and the consequent $\delta^{13}C_{kerogen}$ of source rocks may be the carbon isotope fractionation during photosynthesis. It was suggested that there were two processes that control isotopic fractionation: 1) the process in which carbon enters the intracellular gas chamber; and 2) the reaction process with carboxylase. During the photosynthesis, not all of the carbon in the intracellular gas chamber is fixed; some of the carbon is released to the external environment via respiration in a process known as carbon leakage (Mukherjee and Moroney, 2011). Previous studies have shown that the flora with low carbon leakage has low carbon isotope fractionation and heavier carbon isotopic composition (Surif and Raven, 1990). Detailed studies on the carbon leakage during photosynthesis of micro-planktonic and macro-benthic algae indicated that the carbon leakage of micro-planktonic algae is generally less than that of benthic algae (Sharkey and Berry, 1986; Surif and Raven, 1990). Thus, benthic algae have the higher carbon isotope fractionation and will result in lower $\delta^{13}C$ values of benthic algae even if they utilize similar carbon species those are similar to species utilized by planktonic algae.

5.2 Implications for the Lower Paleozoic oil-source correlation in the Tarim basin

As discussed above, the $\delta^{13}C_{kerogen}$ of hydrocarbon source rocks with different original organism assemblages varied significantly, and the $\delta^{13}C_{kerogen}$ of source rocks with benthic algae were lower than −34‰, whereas they were higher than −30‰ for source rocks with planktonic algae in the northern Tarim basin. Tissot (1984) suggested that the $\delta^{13}C$ values of crude oil are slightly lower than the $\delta^{13}C$ values of kerogen from source rocks. Therefore, original organism assemblages in source rocks and their $\delta^{13}C_{kerogen}$ values will offer a new perspective for oil-source rock correlation.

Based on the statistical data of oil in Tarim Basin, the $\delta^{13}C$ values of oils sourced from the Cambrian ranged from −29‰ to −26‰, such as the oils from wells TD-2, TS1, and T904. In contrast, the $\delta^{13}C$ of oils sourced from the Later Ordovician in the Tahe, Lunnan, and Halahatang oil fields exhibited low $\delta^{13}C$ values, ranging from −34‰ to −31‰ (Fig. 5). Compared with the $\delta^{13}C_{kerogen}$ of hydrocarbon source rocks with different original organism assemblages in the four sections, it is clear that the $\delta^{13}C$ values of oils sourced from the Later Ordovician in the Tahe, Lunnan, and Halahatang oil fields were all lower than the $\delta^{13}C_{kerogen}$ of the Ordovician Heituao and Shaergan Formations source rocks, in which the original organism assemblages were planktonic algae (Fig. 5). Therefore, it is plausible that the oils exploited in the Tahe, Lunnan, and Halahatang oil fields were generated possibility from the Ordovician planktonic algae.

As for the oils sourced from the Cambrian, their $\delta^{13}C$ values are all higher than the $\delta^{13}C_{kerogen}$ of the Cambrian hydrocarbon source rocks with benthic algae but are largely lower or equal to the $\delta^{13}C_{kerogen}$ of the Cambrian Yuertusi Formation with planktonic algae in the Sugatebulake section (Fig. 5). Therefore, these results suggested that the Cambrian oils were only from the source rocks with planktonic algae rather than those with benthic algae because the $\delta^{13}C$ values of crude oil should be slightly lower than the $\delta^{13}C$ values of kerogen from their source rocks (Tissot, 1984). These results seem to confirm the major contribution of planktonic algae for the

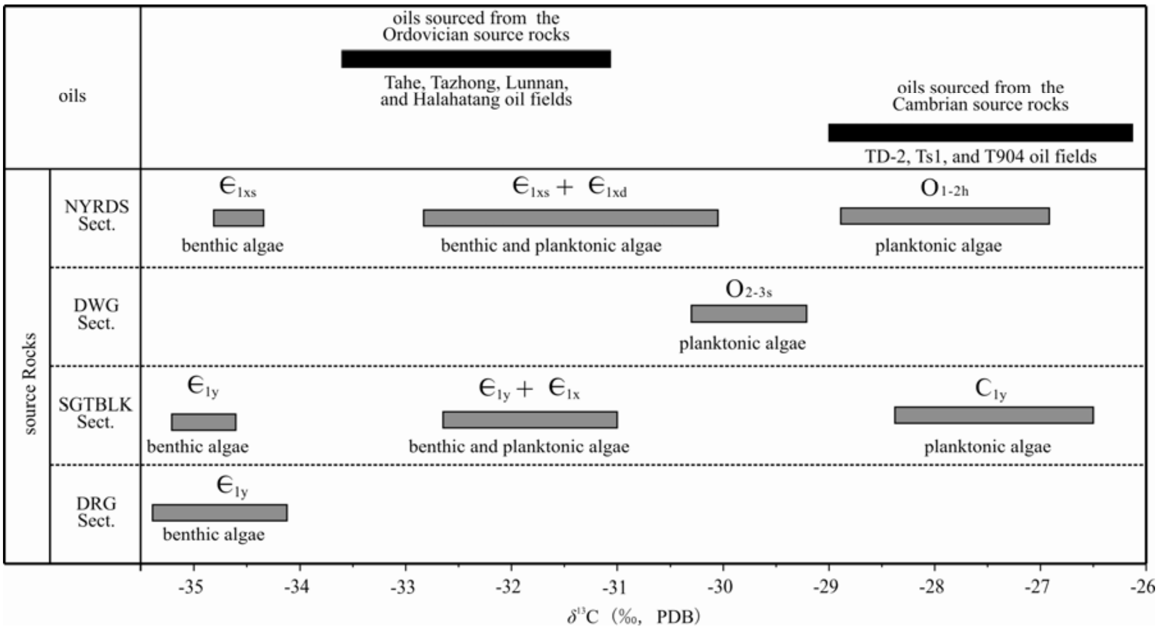

Fig. 5. The Lower Paleozoic oil-source correlation in the Tarim basin based on the original organism assemblages and carbon isotopic compositions.
NYRDS Sect.: The Nanyaerdangshan section; DWG Sect.: The Dawanggou section;
SGTBLK Sect.: The Sugatebulke section; DRG Sect.: The Dongergou section.

Cambrian and Ordovician crude oil exploited in the Tarim. However, the hydrocarbon generating stimulation of extant benthic algae showed that benthic algae also have hydrocarbon potential (Wu Qingyou, 1988; Wang Kaifa et al., 1994; Song Yitao and Li Shu, 1995), oil with lower δ^{13}C values (≤−34‰) has not yet been observed; this might imply that either the oil generated from the Cambrian benthic algae has not yet been exploited or that the oils were all thermally cracked to gas. The petroleum sourced from the Cambrian benthic algae should have great exploration potential, which requires further studied in more detail.

6 Conclusions

(1) The original organisms in the Lower Cambrian were mainly benthic algae but planktonic algae dominated the Upper Cambrian. In the Lower Ordovician, the planktonic algae were the major original organisms.

(2) The $\delta^{13}C_{kerogen}$ of source rocks dominated by benthic algae is generally lower than those of source rocks dominated by planktonic for the Lower Paleozoic in the Tarim Basin. The carbon species utilized by algae and carbon fractionation during photosynthesis might be the major factors that control the $\delta^{13}C_{kerogen}$.

(3) The original organism assemblages dominated by planktonic algae had an important contribution for the Lower Paleozoic oils exploited in the Tarim basin as so far, and the petroleum sourced from the Cambrian benthic algae might be of great exploration potential, and need detailed studies.

Acknowledgments

We thank Professors Li Maowen, Qin Jianzhong, Chen Qianglu from Wuxi Research Institute of Petroleum Geology, SINOPEC for constructive discussions in this study. We are grateful to Drs. Chu Chenglin and Yang Xin (Wuxi Research Institute of Petroleum Geology, SINOPEC) for assistance with fieldwork. This study was jointly funded by National Natural Science Foundation of China (Grant No. U1663201, 41472099 and 41872155), the Strategic Priority Research Program of the Chinese Academy of Science (Grant No. XDA14010404) and CNPC innovation Foundation (2016D-5007-0102).

Manuscript received Apr. 11, 2018
accepted Jul. 27, 2018
edited by Liu Lian

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