Chinese Science Bulletin 2004 Vol. 49 Supp. Ⅰ 1—9

A comprehensive review concerning the problem of marine crudes sources in Tarim Basin

WANG Zhaoming & XIAO Zhongyao

Institute of Exploration, Development and Research under Tarim Oil Field Branch Company, Kuerle 841000, China
Correspondence should be addressed to Wang Zhaoming (e-mail: xiaozhy567@vip.sina.com)

Abstract **The issue of source of oil/gas in the platform basin area in Tarim Basin has been debated for a long time, and the debate is focused on whether the marine oil/gas resources that have been discovered in the basin were originated from hydrocarbon source rocks in the Cambrian-Lower Ordovician or in the Mid-Upper Ordovician. In this paper a summary was made in regard to the major points and supporting data by the predecessors, and a discussion was conducted toward the core issues related to the study on the oil source in the Tarim Basin area, such as choice of correlation parameters, influence of maturation and physical differentiation on oil source correlation parameters, and geological and geochemical significance of these relevant correlation indices. It is quite probable that different interpretation results could arise from the oil source correlation due to choice of parameters severely affected by the thermal maturation and physical differentiation effect, and insisted that only those parameters that come with clearly defined geochemical significance and are less affected by thermal maturation and variations occurring during secondary evolution process are valid ones. The marine crude in Tarim Basin covers contributions that were originated from two sets of hydrocarbon source rocks as mentioned above but dominated by the one from the Mid-Upper Ordovician hydrocarbon source rocks. Here oil of mixed sources occurs extensively, and crude from Cambrian sources was also discovered. It is suggested that for further study on the origin of marine crudes in Tarim Basin, the parameters used for correlation of oil sources shall be optimized, and a comprehensive set of geological and geochemical methods shall be adopted for this purpose.**

Keywords: Tarim Basin, marine crudes, biological marker, oil/gas source correlation, oil source.

DOI: 10.1360/04wd0335

Tarim Basin is a large scale superimposed basin that contains multiple sets of hydrocarbon source rocks, where the formation and distribution of oil/gas reservoirs are closely related to many different factors such as the multiple tectonic movements suffered by the basin, the multi-stage formation, migration, accumulation, destruction and adjustment processes and a variety of secondary geochemical and physico-chemical changes. When these factors were combined together, they would result in the complexity of the basin and created great difficulty toward the study on the issue of marine oil/gas sources in the basin.

A great number of well-known geochemists in China have carried out researches concerning the marine crude oil sources in the Tarim platform basin area, and raised many insightful viewpoints. Generally, many of the points tend to deem that the marine crude originated from the Cambrian-Ordovician hydrocarbon source rocks. However, the academic contentions are focused on which plays the dominant role and which plays the secondary role as far as the two sets of hydrocarbon source rocks in the platform basin area (i.e. the Cambrian-Lower Ordovician hydrocarbon source rocks and Mid-Upper Ordovician hydrocarbon source rocks) are concerned. It is well known that during oil/gas appraisal and exploration determination of the exploration target stratum and study on oil/gas reservoir formation rules as well as oil/gas distribution characteristics, etc. are closely related to oil sources, and the issue of the marine crude oil sources in the platform basin areas has already become a focal point in containing the exploration tempo, affecting decision-making related to oil/gas exploration and improving the rate of success in prospecting, as well as a doubtful and difficult point that needs to be solved firstly in oil/gas resource appraisal and economic assessment in exploration areas, etc.

In regard to the points mentioned above, this study is based on the research results of the previous scholars, their strongpoints and shortcomings, the geological and geochemical characteristics of the two sets of hydrocarbon source rocks as well as the newest achievements made in prospecting. Some understandings and ideas will then be proposed concerning some relevant issues, and the authors here hope that they can help to clarify the way of thinking toward understanding the marine oil/gas sources in Tarim Basin and to provide some valuable references for further research in the related aspects.

1 History and status of study on oil/gas sources in platform basin areas

The issue concerning the oil/gas sources in Tarim Basin area has been debated for some time. But generally speaking, study on oil/gas source is closely related to the exploration process of the oil/gas resources in the basin.

From the discovery of the Shacan 2 oil/gas reservoir in 1984 to now, the study on the oil/gas source issue can be divided into three stages. Stage one lasts from 1984 to 1989. With oil streams of commercial value being discovered and tested at Shacan 2, Lunnan 1, Lunnan 2 and Yingmai 2 wells in succession, at the Symposium on Exploration Technology in the Tarim Oil Field held in 1989, the experts who participated in the meeting generally believed that the dominant oil source rocks in Tarim Basin were Cambrian-Ordovician, and did not regard the oil source issue as a major one for exploration in the Tarim Basin. However, with the successive discovery of high paraffin crude (with paraffin content being 9%—18%) in the Ordovician weathering crusts in Lunnan 8, Lunnan 14, Lunnan 19 and Sha 14 wells, etc. from 1989—1990, scholars began to doubt the point that dominant oil source rocks were in the Lower Paleozoic erathem, and the oil source study entered its second stage. Based on the discovery of a great amount of high paraffin crude and the fact that the maturity of Cambrian source rocks is too high while that of the Ordovician source rocks is too low, as well as the results that the ratios of pristane over phytane in the crudes and the compositions of steranes are close to those of Carboniferous dark-colored pelites and marls, some scholars held that the marine oil in the Tarim Basin might be originated from multiple sources and the Carboniferous system of alternating continental and oceanic facies be most probably the dominant oil source layer[1]. Meanwhile, the results of the State Key Brainstorm Research Project in the 8th five-year plan period demonstrate that there is another point of view, which holds that marine homonemeae organic substance can also result in the formation of high paraffin crude, therefore, the dominant oil source for the Tarim Basin marine crude shall be the Cambrian-Ordovician[2], while the contribution from the Carboniferous rocks is rather limited[3]. At the third stage that lasts from 1996 up to now, more and more core samples and other information can be collected with the progress of the exploration work, which will undoubtedly provide better conditions for the study on the oil source issue. Because no favorable source rocks in the Carboniferous were ever drilled across in the vast area in the east of the basin, the Carboniferous rocks are not likely the dominant hydrocarbon source rocks in the east of the basin. As a result, the Cambrian-Ordovician rocks can be reconsidered as the dominant hydrocarbon source rocks, and the contentions can thus be focused on which form the main contribution and which form the minor contribution toward the formation of the existing oil/gas reservoirs as far as Cambrian-Lower Ordovician and Mid-Upper Ordovician hydrocarbon source rocks are concerned. No definite answers can be reached so far.

More than a decade of research was carried out on the Tarim Basin oil sources. People might ask why the conclusions are so different from one another as they are simply based on the same set of indicators for oil source correlation including biological marker parameters and carbon isotope compositions, etc., then whether it is due to different ways of thinking or to problems of research methods adopted. Here a reinterpretation about the processes of relevant different understandings is required.

2 Viewpoints and supporting data

(ⅰ) Marine crudes mainly originated from Cambrian rocks: Viewpoint and evidences. Based on characteristics of light, medium and heavy biological markers as well as petroleum geological characteristics, Zhao[4] thought that the marine crudes in the platform basin area originated from mixed sources, with the Mid-Lower Cambrian systems being the dominant. A comparison among different fractions in terms of oil/gas source study demonstrates that among the light hydrocarbon components in the Tarim platform basin area, the solution gas in the gas reservoirs and crude in the Tabei and Tazhong uplifts is mainly associated with the Cambrian sapropel-type hydrocarbon source rocks, only the solution gas in the Ordovician crudes in the northern slope of the Tazhong area (e.g., Tazhong 45) mainly originated from the Type III Ordovician hydrocarbon source rocks and can hence be termed "humic-prone type" gas (with the $\delta^{13}C_2$ value generally being −33‰— −37‰, with a mean at −35.7‰). The sapropel-type gas has a $\delta^{13}C_2$ value generally smaller than −40.0‰, which indicates that the contribution from the Ordovician hydrocarbon source rocks is not significant, otherwise the solution gas in the crude shall be able to exhibit characteristics of Ordovician hydrocarbon source rocks in the minimum. A comparison in compounds with moderate molecular weight demonstrates that major differences exist between the crude originated from the Cambrian hydrocarbon source rocks and the crudes from the Ordovician hydrocarbon source rocks: (1) The former has a Pr/Ph generally smaller than 1.2, and is characterized by $Pr/n\text{-}C_{17}<Ph/n\text{-}C_{18}$, while the latter shows the opposite; (2) The former shows lower concentration of low-carbon number triterpanes, and is characterized by a ratio of less than 0.65 for $(C_{19}+C_{21}+C_{22})/(C_{23}+C_{24})$ in triterpanes, while the latter shows the opposite. Results from study on high-carbon number compounds show characteristics of mixed sources for the crudes.

Bao et al.[5] and Wang et al.[6] acquired their understandings on the marine oil/gas sources in the Tarim Basin area mainly from comparative analyses of the compositions of the biological marker compounds related to two sets of hydrocarbon source rocks. Differences between the two sets of hydrocarbon source rocks are obvious: for the Cambrian hydrocarbon source rocks, indicators such as C_{15}-8β(H)-drimane/C_{16}-8β(H)-homodrimane, C_{24}-tetracyclic terpane/C_{26}-tricyclic terpane, total triterpane/total hopanes, C_{27}-/C_{29}-steranes are generally higher than those for the Mid-Upper Ordovician hydrocarbon source rocks, while the relevant ratios for marine crude are close to those for the Cambrian hydrocarbon source rocks. Consequently, it can be concluded that the crudes mainly originated from the Mid-Lower Cambrian systems[4—6].

The study by Wang et al.[7] holds that, the origin study concerning the heavy oil in the west of the Lunnan area is directly related to an accurate understanding about the oil sources in Lunnan area and even in the entire platform basin area, and it appears that the biological marker compounds in the heavy crude show characteristics of the Mid-Upper Ordovician hydrocarbon source rocks[8—12]. However, if the Mid-Upper Ordovician hydrocarbon source rocks were considered as the oil/gas sources simply based on this evidence, the point thus reached would not be able to explain the following issues:

(1) Hydrocarbons were generally formed in the later stage in the Mid-Upper Ordovician hydrocarbon source rocks of platform basin facies, and the oil/gas thus formed would not be accumulated in reservoirs until the Himalayan epoch. As geological conditions for degradation and destruction virtually did not exist in the later stage, the crude would not undergo a process of destruction, hence not occur in the form of heavy crude. Actually it should be normal oil. Since the amount of heavy crude resource is huge in the west of Lunnan area inclusive of the Tahe Oil Field, this would be virtually impossible with the Mid-Upper Ordovician hydrocarbon source rocks being considered as the oil/gas sources even if localized destruction did have happened.

(2) Light hydrocarbon is hard to be detected in heavy crude, which is symbolic of dissipation and destruction of heavy crude and indicates that heavy crude did not accumulate to form reservoirs until the Himalayan epoch and that the heavy crude would be resulted from mixing of the normal oil from the Mid-Upper Ordovician rocks and the biodegraded oil from the Early Cambrian rocks, this is simply because even if normal oil was mixed up with biodegraded oil, light hydrocarbon could still be detectable.

(3) The heavy crude area in west Lunnan is closer to the Halahatang depression (this depression was formed in a later time and the oil formation in the Mid-Upper Ordovician hydrocarbon source rocks is also late). So if the heavy crude originated from the Mid-Upper Ordovician hydrocarbon source rocks in Halahatang depression, and was resulted from later stage destruction, then why no heavy crude was formed in the Lunnan fault dome and in the Sangtamu fault dome? Let alone to say that the Lunnanxi fault had ceased its activity in the early Indosinian while the fractures in the Lunnan fault dome and Sangtamu fault dome were still active in the Yanshanian epoch and the Himalayan epoch, which would be more favorable for formation of heavy crude.

As a result, Wang et al. (2002) concluded that it was hard to elucidate the oil source issue concerning the oil/gas reservoirs in Lunnan area simply by utilizing biological marker compounds. Price et al.[13] also proposed that in regard to multiple sets of hydrocarbon source rocks characterized by great ages and significant span of thermal maturation, oil source correlation study had long been a forbidden zone or constituted a fatal weakness in the study on biological marker compounds. If viewed from the point of the steranes and terpanes in marine crude in Tabei Oil Field, it might be concluded that the crude mainly originated from the Mid-Upper Ordovician hydrocarbon source rocks. However, if viewed from a correlation among the pairs of parameters for hydrocarbon compounds with moderate molecular weight, no matter heavy crude, normal oil, high paraffin oil or condensed oil in Lunnan area, they all show identical fingerprint distribution characteristics (Fig. 1), which demonstrates that it is quite probable

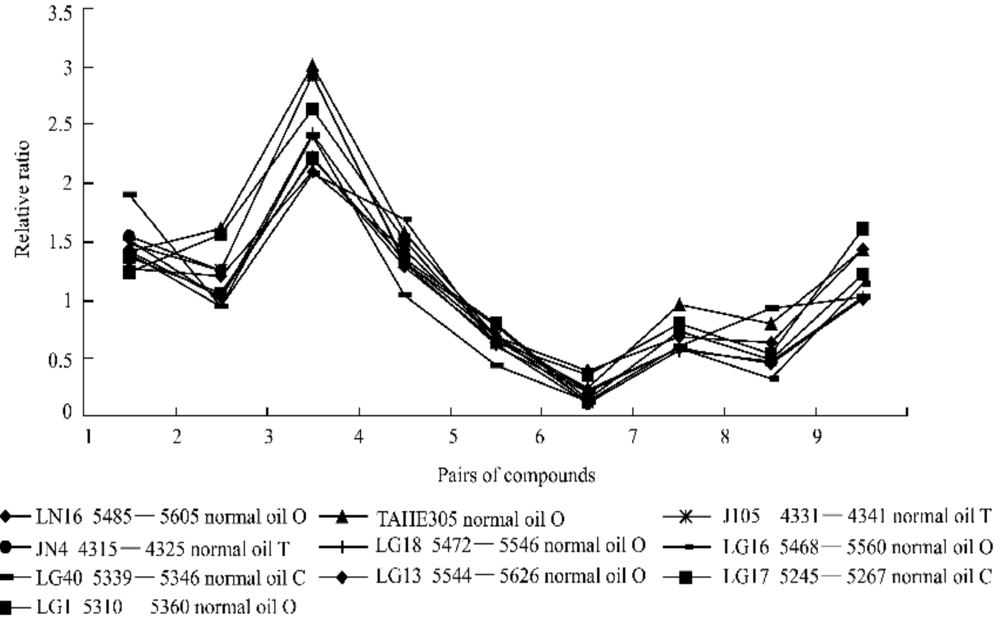

Fig. 1. Correlation of hydrocarbon fingerprints in terms of molecular weight for normal crude in the Tarim platform basin area. 1, *n*-propyl-cyclohexane/isodecane; 2, 2-methyl-nonane/3-methyl-nonane; 3, 2,6-dimethyl-nonane/*n*-pentyl-cyclohexane+1-methyl-decane; 4, 2-methyl-undecane/3-methyl-undecane; 5, 4-methyl-dodecane/3-methyl-dodecane; 6, C5 substituted decane/2,6,10-trimethyl-dodecane; 7, *n*-decyl-cyclohexane+7-methyl-pentadedane+6-methyl-pentadedane/2-methyl-pentadedane; 8, *n*-undecyl-cyclodexane+5-methyl-heptadecane/2-methyl-heptadecane; 9, 2-methyl-eicosane/2,6,10,14-tetramethyl-nonadecane.

that all these crudes originated from the same source[7].

In regard to the exact source for the Ordovician heavy crude in Lunnan 1 well, Wang et al.[7] thought that judgment could be made based on the results of aromizing isoprenoid study. As this type of compounds was detected in the Ordovician heavy crude in Lunnan 1 well, it can be concluded that the crude shall originate from hydrocarbon source rocks formed under anaerobic and strongly reducing environment. However, this condition cannot be met by the Mid-Upper Ordovician hydrocarbon source rocks in the Tarim Basin. Therefore, only Cambrian-Lower Ordovician hydrocarbon source rocks can be the true source for the Ordovician heavy crude in Lunnan 1 well[7].

Additionally, in regard to the oil discovered in the platform basin area, the bulk oil carbon isotopic and the hydrocarbon compound-specific carbon isotopic characteristics are rather similar to each other, and similar to the geochemical signatures of the Ordovician crude in Lunnan 1 well, indicating that they share the same source. Hence it can be inferred that the crudes in Lunnan area and even in the entire Tarim platform basin area mainly originated from Cambrian-Lower Ordovician hydrocarbon source rocks, while a small amount of crude in the Tazhong area might originate from the Mid-Upper Ordovician sources.

(ii) Marine crudes mainly originated from Mid-Upper Ordovician rocks: Viewpoint and evidences. A convincing evidence demonstrating that the crudes originated from the Mid-Upper Ordovician hydrocarbon source rock is rooted in the understandings concerning the characteristics of distribution of time-marking biological markers in marine hydrocarbon source rocks[8—12]. These researches hold that the relative contents of C_{30}-methylaterane, C_{27}—C_{29} steranes and C_{26}-norcholestane, etc. in the extractants from the organic-rich hydrocarbon source rocks in the Lower Paleozoic erathem in the Tarim Basin obviously vary regularly with the time of the strata. The Cambrian and Lower Ordovician hydrocarbon source rocks are basically distributed in the same way, but are obviously distinct from the Mid-Upper Ordovician hydrocarbon source rock in distribution pattern. From the Cambrian, the Lower Ordovician to the Upper Ordovician hydrocarbon source rocks, the relative abundances of C_{30}-dinosterane and 4α-methyl-24-ethyl-cholestane are drastically decreased, while the contents of C_{27}—C_{29} diasteranes are increased, the abundances of C_{28}-steranes and C_{24}-norcholestane change from strong to weak[8,11]. Here the distribution characteristics of the relative abundances of C_{30}-dinosterane and C_{28}-steranes occur actually on a global scale[8,9,14,15], and triaromaticdinosterane, etc. also show similar regular changes[11]. These compounds are generally source-specific, for example, dinosterane, 4-methyl-24-ethyl-cholestane and their aromizing products mainly originated from the dinoflagellate, Dinophyceae and so on[16], 24-norcholestane is representative of diatom records[17,18], C_{28}-steranes mainly originated from diatom, coccolith and dinophyceae[19]. In terms of the combination of biological markers, ∈-O_1 hydrocarbon source rocks show characteristics of being high in six aspects and low in one aspect, while O_{2+3} hydrocarbon source rocks show distribution mode characterized by being low in six aspects and high in one aspect (Table 1)[8]. Because the parameters listed in Table 1 are basically not affected by thermal maturation or secondary changes[10,11], they were regarded as that can be effectively utilized for research on marine oil/gas sources by some relevant researchers.

A GC/MS/MS analysis toward steroids and terpenoids in the marine crudes in the entire basin demonstrates that the compositions of steroids in the crude are characterized by two modes of combination as listed in Table 1[6—10]. But generally speaking, among the marine crudes, crudes characterized by being high in six aspects and low in one aspect, typical of the Cambrian-Lower Ordovician hydrocarbon source rocks are relatively in lower amount, while crudes characterized by being low in six aspects and high in one aspect, typical of the Mid-Upper Ordovician source rocks predominate. Therefore, it can be inferred that O_{2+3} shall be the dominant hydrocarbon source rocks.

3 Discussion on issues related to oil/gas source study

When the earlier researches were summarized, it can be seen that the parameters used for source correlation of marine oil in Tarim Basin mainly involve two types: One group covers the molecular parameters for biological markers, e.g., Pr/Ph, Pr/n-C_{17} and Ph/n-C_{18} for paraffin hydrocarbons, C_{29}/C_{30}-hopanes, Ts/Tm, gammacerane/C_{30}-hopanes, C_{23}-triterpane/C_{30}-hopanes, C_{24}-tetracyclic terpane/C_{30}-hopanes, C_{19-21}-triterpane/C_{23-24}-triterpane, drimane/homodrimane for terpanes, relative contents of C_{27}-C_{28}-C_{29}-steranes, diasterane/normal steranes, dinosterane/methylsterane for steranes, as well as characteristics of the contents of biological marker compounds, and so on; the other group of parameters reflects the average chemical compositions or the general characteristics of a crude, including carbon isotope compositions, absolute contents of biological markers, etc. Nevertheless, all these parameters are influenced to different degrees by a series of geological and geochemical factors. Then which parameters can be used to effectively reflect the difference in oil/gas source? Further discussion will be made in this paper.

(i) Influence of maturation on oil/rock correlation parameters. The differences in compositional characteristics of compounds in between the Cambrian-Lower Ordovician and the Mid-Upper Ordovician hydrocarbon source rocks in Tarim Basin were derived from analysis under the current degrees of maturation for hydrocarbon source rocks. But as a matter of fact, the two sets of hydrocarbon source rocks show big differences in terms of

Table 1 GC/MS/MS characteristics of ∈-O_1 and O_{2+3} effective hydrocarbon source rocks and their derivative crudes in Tarim Basin and their significance (according to Li et al., 1999)

Classification	Cambrian-lower Ordovician	Mid-upper Ordovician
Biological markers characteristics	high in dinosterane; high in 4-methylsterane; high in C_{26}-24-norcholestane (diatom progenitors were developed in ∈-O_1, and the environment is similar to that for the Dinosterane progenitors); high in gammacerane (the bottom layer water is highly reducing); high in C_{28}-steranes (the decrease in contents was regarded as being relevant to the ever-increasing phytoplankton population including diatom and coccolith).	Gloeocapsomorpha type or diluted Gloeocapsomorpha type O_{2+3} oil source rocks are rich in diasteranes on a global scale; As influenced by Gloeocapsomorpha the abundance of alkylcyclohexanein oil source rocks is very high; In regard to hydrocarbon-generating characteristics of Gloeocapsomorpha, low carbon number ($<C_{20}$) *n*-alkanes predominate, while within a specific scope odd number *n*-alkanes predominate, alkylcyclohexane shows high abundance, while isoprenoid hydrocarbon low abundance; Diluted gloeocapsomorpha-type oil source rocks are characterized by greater amount of input of photosynthetic green sulphur bacteria.
Biological source characteristics	Progenitors of phytoplankton population like dinoflagellate, dinophyceae, diatom, coccolith and so on gradually became feeble and died in (O_{2+3} but again began).	Gloeocapsomorpha, photosynthetic green sulphur bacteria
Characteristics of time-specific biological marker combination in crude	Being high in six aspects and low in one aspect High in dinosterane dinosteane/(dinosterane+3- methylsterane)≥0.2 High in 4-methylsterane 4-methylsterane/(4-+3-methylsterane)≥0.35 High in C_{26}-24-norcholestane,24-/(24-+27-)>0.3 High in C_{26}-24-nordiacholestane 24-nor/(24-nor+27-nor) nordiacholestane>0.25 High in C_{28}-steranesC_{28}/(C_{27}+C_{28}+C_{29})-steranes >20% High in gammacerane $\gamma/C_{30}H$>0.1 Low in diasterane C_{27}-diasterane/C_{27}-steranes<1	Being low in six aspects and high in one aspect Low in dinosterane Dinosterane/(dinosterane+3-methylsterane) <0.15 Low in 4-methylaterane 4-methylaterane/(4- + 3-methylaterane)<0.25 Low in C_{26}-24-norcholestane,24-/(24-+27-)<0.2 Low in C_{26}-24-nordiacholestane Dia 24 nor/(dia24-nor+dia27-nor) nordiacholestane<0.2 Low in C_{28} steranesC_{28}/(C_{27}+C_{28}+C_{29})-steranes <20% Low in gammacerane $\gamma/C_{30}H$<0.05 High in diasterane C_{27}-diasterane/C_{27}-steranes>1

the thermal maturation, and the R_o value difference can generally be higher than ca. 0.8%.

The difference in the thermal maturation can severely affect the coordinate indicators. For example, terpenoids such as sesquiterpenoids, tricyclic terpane and hopanes, in marine crude are generally associated with the biological source input of bacteria[20—22]. With the increase in thermal maturation, the ratio of triterpane/hopanes will continue to be increased[23]. Similar results can also be obtained for long-chain hopane compounds. Peters et al.[20] noticed that with the increase in the thermal maturation, the content of C35-homohopane would be decreased while the abundances of short-chain hopanes will be increased; Wang et al.[24] also pointed out this type of occurrence in geological samples.

Results of comparative analyses toward crudes of identical sources and characterized by consistent chemical compositions in the Hudson oil field and its related areas in Tarim Basin also demonstrate that the ratios of some compounds, such as triterpane/hopanes, C_{15}-drimane/C_{16}-drimane, C_{19}-C_{22}/C_{23}-C_{26}-tricyclic terpane, and C_{30}-hopanes/C_{32+}-hopanes, show good positive correlative relationship (Fig. 2). Even though Ts/Tm is generally affected by both sedimentary facies and thermal maturation[25—27], the difference in Ts/Tm is mainly controlled by thermal maturation as far as crudes of identical sources are concerned[28]. As a result, these coordinate parameters are influenced to great degrees by the thermal maturation, and generally show remarkable increase with the increase in the thermal maturation.

(ii) Influence of physical differentiation on oil source correlation indices. Physical differentiation mainly refers to migration-related fractionation, evaporation-related fractionation, air cutting and gas washing-related fraction, etc. Here migration-related fractionation is a common physical fractionation process during the oil/gas reservoir formation process and oil/gas readjustment process, and is an important factor that affects the chemical compositions of oil and gas. These fractionation processes can result in drastic variations in oil/gas compositions, and can even sometimes destroy a great number of information inherited from the source rocks[29], and meanwhile leads to changes in biological marker parameters. Vicinal homologues (or parahomologues, e.g., cyclanes characterized by long side chain vs. short side chain) will show variations in contents with changes in molecular weight. As can be seen from the correlation factors including fractionation coefficients that can reflect fractionation intensity and some geochemical parameters listed by Dzou and Hughes (1993), not only the API value and ratio of saturated hydrocarbon to aromatic hydrocarbon of a crude will be affected by migration-related fractionation, Pr/Ph, drimane/homodrimane, diadrimane/drimane, etc. will also be strongly influenced by migra-

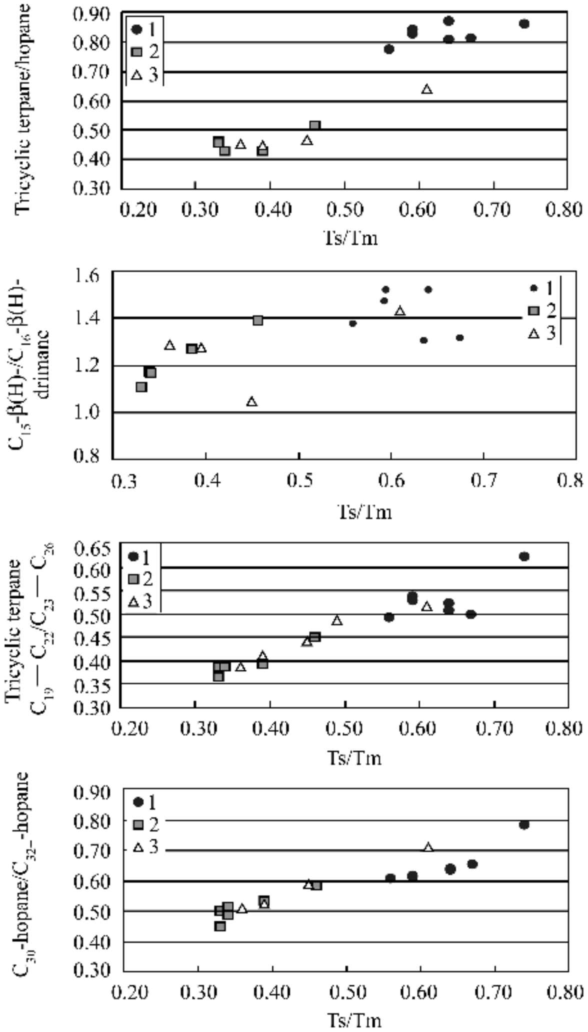

Fig. 2. Diagrams showing the ratios of Ts/Tm vs. relevant terpenoid compounds in crude of same sources in Hudson and its related areas (Xiao, 2002). 1, Crudes from Hudson; 2, crude from Tahe oil field; 3, crudes from Xiang 3, LN1, LN11, LN18 wells.

tion-related fractionation, which will certainly shaken the foundation on which these parameters can be used for oil/source correlation.

The triterpane/hopanes ratio will also be affected by migration-related fractionation[30]. Experiments by using Al_2O_3 column to simulate oil migration in laboratory conditions indicate that triterpane is faster than hopanes in terms of effluent speed[27]. As a matter of fact, compounds of different molecular weights, polarities, and stereochemical configurations will show different behaviors in terms of adsorption and desorption during the processes of being discharged out of their source rocks (primary migration) or being transported through the carrier layers (secondary migration)[31]. Here differences in molecular size and polarity are important factors that control the degree of differentiation of indicators during migration process, while difference in molecular configuration plays a secondary role or shows no variation[32].

Owing to the characteristics of hydrocarbon generating-related thermal evolution and reservoir formation in the marine facies hydrocarbon source rock in Tarim Basin, air cutting or gas washing is very common in oil/gas reservoirs, and is an important type of physical differentiation. Researches by Larter and Mills (1991), Meulbroek (1998) and so on demonstrate that after gas washing, the light hydrocarbon fraction of the crude would show corresponding variations, as a result, gas washing can also be used to describe multi-stage geological events or the phase differentiation process resulted from mixing between crude and gas[29,33]. Therefore, this type of phase differentiation process can lead to changes in fluid compositions, but may signifies difference between oil and gas sources in terms of oil/gas source study.

Additionally, migration-related fractionation will also exert influences on carbon isotope compositions, even though this kind of influence could be as low as around 1‰—2‰[29]. But as far as oil originated from the same marine facies source rocks in the Lower Paleozoic is concerned, this kind of difference merits serious consideration.

(iii) Influences from other factors. The Cambrian hydrocarbon source rocks in Tarim Basin underwent large-scale hydrocarbon effluence at the end of Silurian, which resulted in formation of paleo oil/gas reservoirs. At the end of Devonian, the strata were intensively uplifted and eroded, and the paleo oil/gas reservoirs suffered from a series of destruction such as biodegradation, water washing and oxydation, etc. In Tabei and Tazhong in the Tarim Basin, most of the high density crudes, such as LN1 (O), LN15 (O), S46 (O), S65 (O), TZ11 (S) crudes, and part of the low density crudes, such as TK301 (O), TK305 (O), and Tazhong 47 (S) crudes, all contain abundant 25-norhopane, and the *n*-alkanes are all complete, which helps to explain that the oil reservoirs were resulted from refilling of earlier stage oil reservoirs that had suffered from intensive destruction. The Silurian asphaltic sand that was extensively distributed in Manjia'er depression and its peripheral areas was also resulted from shallow layer hypergene oxydation and degradation of paleo oil reservoirs. Therefore, in oil source study we shall not only focus our attention on the influence of oxydation and degradation on the compositions of hydrocarbons in the reservoirs but also identify the similarities and differences in oil/gas source characteristics and biological marker combination characteristics resulted from two (or multiple) filling processes.

(iv) Geochemical significance of aryl-isoprenoids. As diagenetic compounds of carotenes, aryl-isoprenoids are generally low in contents in both hydrocarbon source rock and crude oil, since many other compounds can run away together with this type of compounds. They can be systematically detected on *m*/*z* 133 or *m*/*z* 134 mass chromatograms based on the distribution characteristics of compounds with different carbon numbers. This type of compounds were mainly resulted from photosynthetic green sulphur bacteria under the anaerobic and strongly reducing environment, and can thus be markers indicative of stratification of strongly reducing water bodies. A typical example of such modern deposition environment for analogy purpose is the Black sea. Study results on such type of compounds have already been published both at home and abroad[34—39].

Peng et al. (2002) and Sun et al. (2003) detected aryl-isoprenoids of higher abundances in crude and reservoir bitumen in Lunnan area[40,41]. Wang et al. (2003) published similar results on Tahe crude[12]. But can this type of compounds be considered as direct evidence to demonstrate that the marine crude in the Tarim Basin originated from the Cambrian rocks? This merits further discussion on our part.

It should be admitted that this type of compounds shows clearly defined environment signatures. However, the aryl-isoprenoids in the marine hydrocarbon source rocks in the Tarim Basin generally show significant variations in both contents and distribution. According to results by Wang et al. (2003), this type of compounds show low contents in the Cambrian and Ordovician rocks in Keping area, extremely low contents in the Cambrian and Ordovician rocks in Tadong 1 and Kunan 1 wells, low contents in the O_{2+3} laminated pelitic limestones in Z12 well, but high contents in the O_{2+3} pelitic limestones in TZ30 well, relative high contents in the O_{2+3} and O_1y gray-colored brecciate limestones in S86 well[12]. This is to say that conditions for formation of this type of compounds are not restricted to the Cambrian-Lower Ordovician hydrocarbon source rocks. In the condensed oil in Tabei area, the relative enrichment of this type of compounds demonstrates that they are related not only to the deposition characteristics of hydrocarbon source rocks but also to their own strong anti-degradation capability.

In summary, when the chemical composition and characteristics of crudes and their hydrocarbon source rocks are to be used for oil/gas source correlation, a comprehensive research and analysis shall be conducted based on a full consideration of and detailed study on a variety of parameters and their impact factors as well as on the regional petroleum geological conditions.

4 Implications of the newest prospecting results on oil/gas source study

As was discussed above, study on the oil/gas sources in Tarim Basin is closely associated with the progresses in oil/gas exploration. The discoveries of the Cambrian oil reservoir in Tadong 2 well and the oil reservoir in Silurian sandstone lens in Tazhong 62 well Tarim Basin serve as important clues for an in-depth study on the marine oil/gas sources. An analysis on the regional petroleum geological conditions and the reservoir formation processes indicates that the crudes in Tadong 2 well and Tazhong 62 well shall be resulted from the Cambrian hydrocarbon source rocks, while GC/MS/MS results also indicate that the compositions of the steranes and methyl triaromatic steranes in the crude of Tadong 2 well are rather consistent with those of the Cambrian hydrocarbon source rocks in this well[11]. In the *m*/*z* 217 mass chromatograms, the distribution of crude for Tazhong 62 well is consistent with that for Tadong 2 well (Fig. 3(a) and (b)). The abundance of C_{28}-steranes tends to be higher among steranes, while the abundance of diasterane tends to be lower. The relative content of Gammacerane is relatively high among triterpenes and is roughly comparable to that of C_{31}-hopanes. This kind of distribution characteristics are basically consistent with the results by Li et al., Zhang et al., and Wang et al.[8—12]. While being distinct from a great majority of marine crude samples in the basin, these crude samples are generally consistent with the crude originated from the Mid-Upper Ordovician rocks in Tazhong 169 well in steroids and terpenoids compositions (Fig. 3(c)). The discovery of the crudes in Tadong 2 well and Tazhong 62 well and research results on the hydrocarbons may indicate at least one fact, i.e. the crude that shows characteristics of being high in six aspects and low in one aspect, typical of the Cambrian hydrocarbon source rocks, shall originate from the Cambrian hydrocarbon source rocks.

5 Summary and conclusions

In conclusion, the marine oil/gas in Tarim Basin shows complicated formation mechanisms, the hot debate on the oil source issue mainly lies in the choice of correlation indices and the ambiguities in geochemical signatures for some compounds as far as oil/gas source study is concerned. The progresses made in analytical technologies and the expansion in prospecting frontiers will undoubtedly be helpful in solving the conundrum. However, correct scientific way of thinking will also help to speed up the course for the final solution of this problem. The authors hold that in the study on the issue concerning marine oil source in Tarim Basin special attention shall paid on the following aspects:

(i) Indices for correlation shall be the ones less affected by thermal maturation, and migration, since they can better reflect the difference in hydrocarbon generating materials between the two sets of source rocks. Moreover, results of correlation among various indices and effects of their application to Tarim Basin case shall be summarized.

(ii) Cutting-edge analytical technologies, such as GS-MS-MS, hydrocarbon compound-specific C and H isotopes, macromolecular splitting, and Ar-Ar isotope dating, will become means necessary for solving the issue

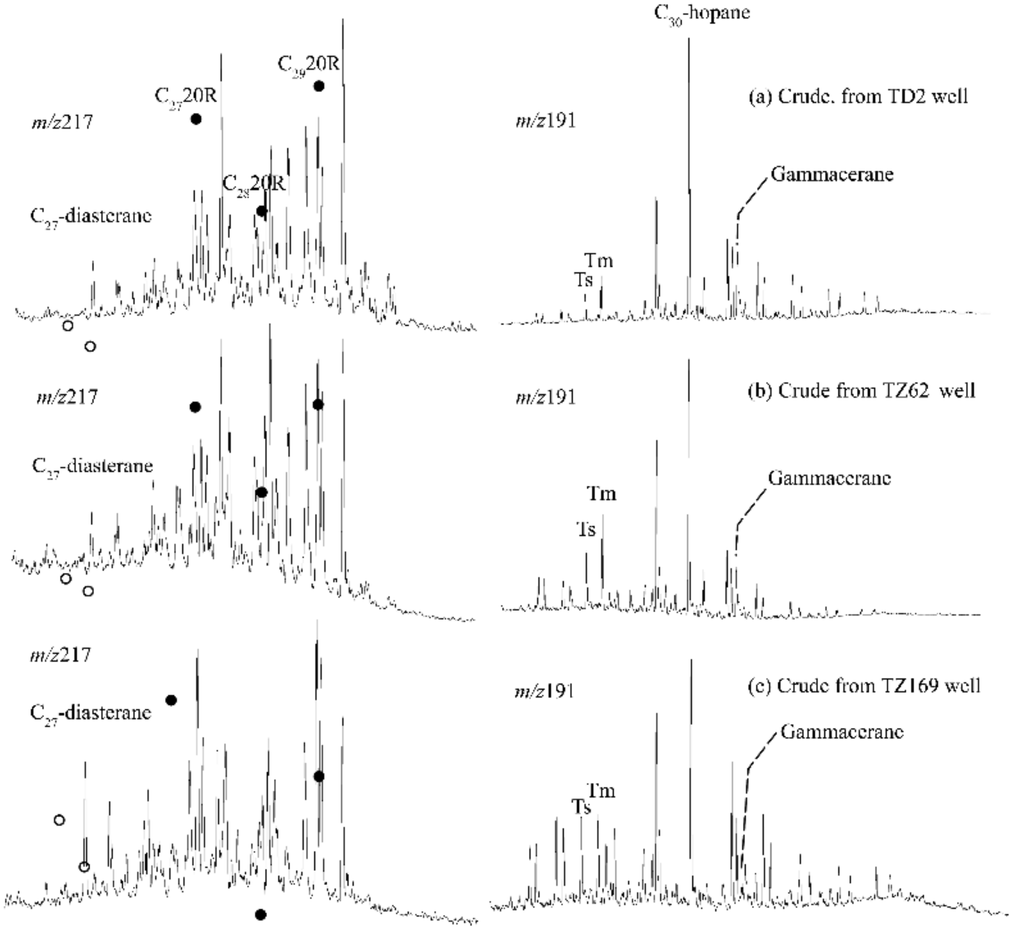

Fig. 3. Compositions of steroids and terpenoids in the crudes from Tadong 2 well and Tazhong 62 well and comparison with those from Tazhong 169 well.

concerning the marine oil source in Tarim Basin.

(iii) An accurate determination of the time for the formation of the marine oil/gas reservoirs in the Tarim Basin will serve as a bridge to solving the oil source issue, this is simply because the differences in thermal maturation and hydrocarbon generation history are the biggest ones between the two sets of source rocks. If the Cambrian-Lower Ordovician rocks are the dominant marine oil source rocks in Tarim Basin, then the effective age for oil/gas reservoir formation would not be later than the Late Hercynian; if the Mid-Upper Ordovician rocks are the dominant marine oil source rocks in Tarim Basin, then the effective age for oil/gas reservoir formation would not be the Yanshanian-Himalayan epoch.

References

1. Wang Huixiang, Xie Zengye, Wang Shejiao et al., Appraisal on the oil source rocks in Tarim Basin and analysis about the oil sources, Party for Comprehensive Geological Research under the Headquarters for Petroleum Exploration in Tarim Basin (in Chinese), 1990.
2. Sheng Guoying, Fu Jiamo, Identification of the Paleozoic oil source rocks and the dominant oil source rocks in Tarim Basin, Guangzhou Institute of New Geological Technology, Chinese Academy of Sciences (in Chinese), 1994.
3. Huang Difan, Liang Digang, Generation and evolution of oil and gas in Tarim Basin, Report of achievements made in the State brainstorm research project in the 8th five-year plan period (85-101-01-04), Beijing Institute for Petroleum Exploration and Development (in Chinese), 1995.
4. Zhao Mengjun, Xiao Zhongyao, Peng Yan et al., New advances in organic geochemical research concerning Tarim Basin, Exploration and Research Center under the Headquarters for Petroleum Exploration in Tarim Basin, 1997.
5. Bao Jianping, Zhu Junzhang, Study on origin and enrichment rules of marine crude in Tarim platform basin area, Jianghan Petroleum College (in Chinese), 2000.
6. Wang Hongjun, Zhang Guangya, Bao Jianping, Discussions on the oil source issue concerning the Carboniferous oil reservoirs in the Hudson area, Exploration and Research Center under the Headquarters for Petroleum Exploration in Tarim Basin (in Chinese), 2000.

7. Wang Tingdong, Xu Zhiming, Lin Feng et al., Study on the mechanism for formation of the oil/gas reservoirs in Lunnan area, Southwest China Petroleum College (in Chinese), 2002.
8. Lin Renzi, Wang Peirong, Xiao Zhongyao et al., Study on the profiles dated with biological markers in northwest China and the ages for the dominant marine oil source rocks in Tarim Basin, China Petroleum University (Beijing) (in Chinese), 1999.
9. Zhang, S. C., Moldowan, J. M., Li, M. et al., The abnormal distribution of the molecular fossils in the pre-Cambrian and Cambrian: its biological significance, Science in China, Series D, 2002, 45(3): 193—200.
10. Zhang, S. C., Hanson, A. D., Moldowan, J. M. et al., Paleozoic oil-source rock correlation in the Tarim Basin, NW China, Organic Geochemistry, 2000, 31: 273—286.
11. Zhang Shuichang, Liang Digang, Li Maowen, Correlation between molecular fossils and oil sources in Tarim Basin, Chinese Science Bulletin, 2002, 47(Suppl.): 16—23.
12. Wang Tieguan, Wang Chunjiang, Zhang Weibiao et al., Geochemical study on formation of the Ordovician oil/gas reservoirs in Tahe oil field, Sinopec Xinxing Northwest China Branch (in Chinese), 2003.
13. Price, L. C., LeFever, J., Dysfunctionalism in the Williston Basin: the Bakken/mid-Madison petroleum system, Bulletin of Canadian Petroleum Geology, 1994, 42(2): 187—218.
14. Tasch, P., Paleobiology of the Invertebrates: Data Retrieval from the Fossil Record, New York: Wiley & Sons, 1980.
15. Hanson, A. D., Zhang, S. C., Moldowan, J. M. et al., Molecular organic geochemistry of the Tarim Basin, Northwest China, AAPG Bulletin, 2000, 84(8): 1109—1128.
16. Moldowan, J. M., Dahl, J., Jacobson, S. R. et al., Chemostratigraphic reconstruction of biofacies: Molecular evidence linking Cyst-forming dinoflagellates with pre-Triassic ancestors, Geology, 1996, 24(2): 159—162.
17. Holba, A. G., Tegelaar, E. W., Huizinga, B. J. et al., 24-norchplestanes as age-sensitive molecular fossils, Geology, 1998, 26: 783—786.
18. Holba, A. G., Dzou, L. I. P., Masterson, W. D. et al., Application of 24-norcholestanes for constraining the age petroleum, Organic Geochemistry, 1998, 29: 1269—1283.
19. Grantham, P. J., Wakefield, L. L., Variations in the sterane carbon number distributions of marine source rock derived crud oils through geological time, Organic Geochemistry, 1988, 12: 61—73.
20. Peters, K. E., Moldowan, J. M., The Biomarker Guide, Interpreting Molecular Fossils in Petroleum and Ancient Sediments, Englewood Cliffs: Prentice Hall, 1993, 230—232.
21. Alexander, R., Rigi, R. I., Noble, R. A., Identification of the bicyclic sesquiterpenen drimance and eduermane in petroleum, J. Chem. Soc. Commun., 1983, (5): 226—228.
22. Ourisson, G., Albrecht, P., Rohmer, M., The microbial origin of fossil fuels, Scientific American, 1984, 251: 44—51.
23. Wang Xinzhou, Thermocompression simulating experiments on immature oil generating rocks, Acta Sedimentologica Sinica (in Chinese), 1983, 1(1): 118.
24. Wang Peirong, Zhou Guangjia, Geochemistry of biological markers, Jianghan Petroleum College (in Chinese), 1996.
25. Palacas, J. G., Petroleum geochemistry and source rock potential of carbonate rocks, AAPG Studies in Geology, 1990.
26. Tissot, B., Welte, D. H., Petroleum Formation and Occurrence, 2nd ed., Berlin: Springer-Verlag, 1984.
27. Zhou Guangjia, Discussions on the effectiveness of application of common indices for biological markers such as steranes and terpanes, in Organic Geochemistry and Oil Generation in Continental Rocks (in Chinese), Beijing: Petroleum Industry Press, 1986, 39—51.
28. Xiao Zhongyao, Geochemical study on reservoir formation in Hade 4 oil field, Ph.D. Dissertation with Institute for Exploration, Development and Research under the Tarim Oil Field Branch Company (in Chinese), 2002.
29. Larter, S., Mills, N., Phase-controlled molecular fractionations in migrating petroleum charges, in Petroleum Migration (eds. England, W. A., Fleet, A. J.), Geological Society Special Publications, 1991, 59: 137—147.
30. Dzou, L. I., Hughes, W. B., Geochemistry of oils and condensates, K. Field, offshore Taiwan: A case study in migration fractionation, Organic Geochemistry, 1993, 20(4): 437—462.
31. Seifert, W. K., Moldowan, J. M., Paleoreconstruction by biological markers, Geochim. Cosmochim. Acta, 1981, 455: 783—794.
32. Peters, K. E., Moldowan, J. M., Effect of source, thermal maturity and biodegradation on the distribution and isomerization of homohopanes in petroleum, Organic Geochemistry, 1991, 17: 47—61.
33. Meulbroek, P., Cathles, L., Whelan, L., Phase fractionation at South Eugene Island Block 330, Organic Geochemistry, 1998, 29, 1-3: 223—239.
34. Summons, R. E., Powell, T. G., Chlorobiaceae in Paleozoic sea revealed by biological markers, isotopes and geology, Nature, 1986, 319: 763—765.
35. Summons, R. E., Powell, T. G., Identification of arylisoprenoids in source rocks and crude oils: Biological markers for the green sulphur bacteria, Geochin.Cosmchim. Acta, 1987, 51: 557—566.
36. Sinninghe Damsre, J. S., Wakeham, S. G., Kohnen, M. E. et al., A 6000-year sedimentary molecular record of chemocline excursions in the Block Sea, Nature, 1993, 362: 827—829.
37. Hartgers, W. A., Sinninghe Damsre, J. S., Requejo, A. G. et al., Evidence for only minor contributions from bacteria to sedimentary organic carbon, Nature, 1994, 369: 224—227.
38. Koopmans, M. P., Diagenetic and catagenetic products of isorenieratene: molecular indicators for photic zone anoxia, Geochimica et Cosmochimica Acta, 1996, 60(22): 4467—4496.
39. Heidy, M. E. Van., A molecular and carbon isotope biogeochemical study of biomarkers and kerogen pyrolysates of Kimmeridge clay facies: Palaeoenvironmental implications, Organic Geochemistry, 1997, 27(7/8): 399—422.
40. Peng Ping'an, Lü Xiuxiang, Diversity of sources, reservoir formation periods and crudes in Lunnan area, Study report on the project on "Formation and Distribution of as well as Enrichment Rules for Oil and Gas in Superimposed Basins in China" for the state 973 project, Guangzhou Institute of Geochemistry, Chinese Academy of China (in Chinese), 2002.
41. Sun Yongge, Xu Shiping, Lu Hong et al., Source facies of the Paleozoic petroleum systems in the Tabei Uplift, Tarim Basin, NW China: Implications from aryl isoprenoids in crude oils, Organic Geochemistry, 2003, 34: 629—634.

(Received August 5, 2004; accepted December 3, 2004)