Molecular fossils and oil-source rock correlations in Tarim Basin, NW China

ZHANG Shuichang[1], LIANG Digang[1], LI Maowen[2], XIAO Zhongyao[3] & HE Zhonghua[1]

1. Key Laboratory of Petroleum Geochemistry, Research Institute of Petroleum Exploration and Development, China National Petroleum Corporation, Beijing 100083, China;
2. Geological Survey of Canada, 3303-33 st., NW Calgary, Alberta T2L 2A7, Canada;
3. Research Institute of Petroleum Exploration and Development, Tarim Oilfield, Kuerle 841000, China

Correspondence should be addressed to Zhang Shuichang (e-mail: sczhang@petrochina.com.cn)

Abstract **The distribution of "molecular fossils" (biomarkers) of steroid compounds in extracts from some specific geologic age in the Tarim Basin have been analyzed and are used as the fingerprints for the oil-source rock correlation. Having been affected by maturation, migration, phase fractionation and biodegradation, not any molecular fossils related to source and environment can be used as the fingerprints for oil-source rock correlation. Some special biomarkers widely existed in the extracts from Cambrian and Ordovician rocks in the Tarim Basin and showed obvious difference in each stratum, including dinosteranes (C_{30}), 4-methyl-24-ethyl-cholestanes (C_{30}) and their aromatized steroids, C_{24}-norcholestanes and C_{28} steranes originated from dinoflagellates and diatom. Few oils such as the heavy oil drilled in the Cambrian reservoir from Tadong 2 well (TD2) correlated well with the extracts from the Cambrian. The amazing similarity of the relative contents of these compounds between the marine oils produced in Tazhong and Tabei uplifts and the extracts from the Upper Ordovician suggests that the Middle-Upper Ordovician is the very likely main source for the marine oils.**

Keywords: molecular fossils, dinosterane, triaromatic dinosterane, 24-norcholestane, dinoflagellate, Cambrian, Upper Ordovician, Tarim Basin.

Molecular fossils, as an independent chemical record and a mutually complementary for hard fossils, are preserved in sediments. Due to the stability of their carbon skeletons and complex "fingerprints" character even in diagenesis and catagenesis, they have been extensively used in the petroleum geochemistry. Correlations obtained from biomarkers fingerprints enable people to understand the origin of oils and their migration from source rocks to reservoirs.

In various biomarkers, terpanes and steranes are two kinds of compounds which are the most widely used for correlating. Terpanes come mainly from prokaryote (e.g. bacteria)[1]. Almost all oils contain terparnes because bacteria exist widely in the sediments. The oils generated from different source rocks deposited under similar conditions often have the analogues terpanes fingerprints[2]. So far, among so many terpenoids compounds discovered, except some compounds with specific structures in terpanes, such as oleanane (angiosperms-specific marker), biaddinanes (angiosperm dammar resins-specific marker) and tetracyclic diterpanes (coniferophyte-specific marker) having source-specific meaning, only few can act as molecular fossils for taxon-specific source indicators. Steranes, derived from hydrocarbon sterols, are indeed of a very ancient lineage. They are sedimentary markers for eukayotes, including plants, algae and animals. Sterols appear to be the chemical gatekeepers for higher life forms. They impart a quasi-structure or shape to cell membranes and form the basic structures for the sex hormones[3].

However, not all the terpenoids and steroid compounds have fossil meaning. Being the indicators of oil-source rock correlation, they should satisfied the following three conditions: (1) specific source; (2) little affected or unaffected by maturation; and (3) little affected or unaffected by secondary alteration (such as deasphalting, biodegradation, thermal alteration in reservoir, water-washing, phase fractionation and geochromatography during migration and within-reservoir).

The Tarim Basin, NW China, is a large, composite basin with numerous ancient petroleum source rocks of different geological ages. The basin might have undergone multiple periods of hydrocarbon generation, accumulation and migration. The resultant complexity of the Tarim Basin makes the study of oil-source rock correlation disputable. Recent disputes are focused on whether the source rock is the Cambrian or the Ordovician. One of the underlying reasons is the inconsistency of parameters for oil-source rock correlation by different researchers and neglecting the three factors as mentioned above. In this paper, combining with the property of source rocks, maturation difference, migration-fractionation during migration and accumulation and biodegradation, the analysis of marine oil-source rocks correlations in the Tarim Basin was carried out carefully by using algae-related steroids compounds composed of higher carbon numbers with equal or near molecular weights. The result shows that only some residud paleo-reservoirs such as the heavy oil found in Tadong 2 well (TD2) from the Cambrian reservoir and natural gas reservoirs in the platform basin are contributed by the Cambrian, whereas the commercial reservoirs discovered in Tazhong and Tabei uplifts up-to-date are mainly contributed by marl that deposited on the slope of the marginal platform in the age of the Middle-Upper Ordovician.

1 Samples and experiments

The rock samples were selected from the core of Cambrian and Ordovician strata in the Tarim Basin. After careful core observation and strict TOC and Rock-eval screening, only marl, limestone and mud/shale samples are rich in organic matters, and samples with TOC more than 0.4% were chosen for the next stage of analysis. These samples are distributed in different sedimentary facies. The Cambrian in wells in the eastern part of the basin, such as Tadong 1 well (TD1), TD2 well and Kunan 1 well (KN1) are under-compensated basin sediments. The Cambrian in Tacan 1 well (TAC1) in the middle of the basin is marginal facies of the evaporated lagoon. The Cambrian from He 4 well (H4) in the western of the basin is the evaporated lagoon and Fang 1 well (F1) is the marginal platform to the slope of the marginal platform. The Heituwa Formation (O_1h), Lower Ordovician in TD1 and TD2 are developed in the under-compensated basin. The Lianglitage Formation (O_3l), Upper Ordovician are developed in a slope of the marginal platform. The analyzed oil samples are selected from almost all kinds of crude oils produced in marine commercial reservoirs from Tazhong and Tabei uplifts and some oils produced in non-commercial reservoirs such as the Cambrian heavy oil in TD2. The brief introduction of all studied samples is listed in table 1.

For the analysis methods and procedure of sample extraction and separation, and biomarker analytical methods see refs. [4, 5].

Table 1 List of all samples in this study

Rock samples			
Age	Representative wells	TOC (%)	Depositional environment
Upper Sinian	eastern part of the basin: TD1	0.90	under-compensated deep-water basin
	eastern part of the basin: TD2, KN1	0.47—4.88	deep-water basin
Cambrian	center of the basin: TaC1	0.70	marginal platform-marginal basin
	western part of the basin: He4, F1, Kang2	0.31—0.57	evaporated lagoon
Lower Ordovician	eastern of basin: TD1, TD2	0.40—7.62	under-compensated deep-water basin
	northern slope of Tazhong (9 wells): TZ6, 12, 53, etc.	0.40—12.82	slope of marginal platform
Upper Ordovician	southern slope of Tabei: LN46, X3	0.86	slope of marginal platform
Crude oil samples			
Heavy oils (d_4^{20} >0.92)			
Tadong: TD2(Cam); West of Lunnan faults: LN1(O), LN11(O), LG9(O); Tahe oilfield: TK401(O), 402(O), S66(O)			
Tazhong oilfield: TZ1(3755 m), TZ11(4314 m, 4411.2 m, 4417—4435 m, S), TZ15(O3), TZ35(CIII)			
Normal oils (d_4^{20} 0.82—0.92):			
Lunnan oilfield: LN2(T), JF100(T), LN44(T), LN32(C); Tahe oilfield: TK301(O), TK303(O), S47(O);			
Hadexun oilfield: HD1(C), HD4(C); Donghetang oilfield: DH4(C), HD1(C); Yingmaili: YM2(O)			
Tazhong oilfield: TZ4(C), TZ401(C), TZ111(C), TZ24(C), TZ44(O), TZ161(C), TZ16(O), TZ11(S)			
Waxy oils: JF123(O), LN14(O), LN8(O)			
Condensates (d_4^{20} <0.82):			
Lunnan oilfield: LN44(O), JF124(C), LN57(T); Tazhong oilfield: TZ6(C), TZ1(C), TZ45(O)			
Others (oil sands and samples without industrial value)			
TZ24(O_{3l}), TZ12(O_1), TZ4(oil sand, S), X3(C, oil stained; O, heavy oil with water), CH2(C, oil stained), YW1(O, oil sand)			

2 Results

(i) Biomarkers distribution in source rocks of different age

Distribution of C_{30} methylsteranes (*m*/*z* 414→231), C_{27}—C_{29} steranes (*m*/*z* M^+→217) and C_{26} norcholestanes (*m*/*z* 358→217) in the extracts from three sets of Low Paleozoic stratas which are rich in organic matter in the Tarim Basin are shown in constract (fig. 1). The relative content of these compounds shows obvious and systematic change with the geologic age. It is clear that the extracts from the Cambrian and Lower Ordovician show a similar distribution, different from that of the Upper Ordovician. From the Cambrian-Lower Ordovician to the Upper Ordovician, the intensities of dinosteranes (4α, 23, 24-trimethyl-cholstane) and 4α-methyl-24-ethylcholestanes of C_{30} steranes decrease dramatically to the degree of trace. Meanwhile, the concentration of C_{27}—C_{29} diasternaes increases and the abundance of C_{28} steranes and 24-norcholestanes decreases (fig. 1). Besides, triaromatic dinosteranes in the extracts show regular changes. Although the reasons for these changes are not clear enough at present, these differences can be used as the good indicators for distinguishing the source rocks among the Cambrian-Lower Ordovician from the Upper Ordovician.

(ii) Oil-source rock correlation

The selection of parameters used for oil-source rock correlation is very important in the Paleozoic basin where multiple source rocks deposit and multiple hydrocarbon accumulations are real clearly. Due to the distinct maturity difference of the source rocks between the Cambrian and Upper Ordovician, maturation will distort the oil-source rock correlation. Meanwhile, hydrocarbon may have a multiple filling history and has undergone obvious migration-fractionation (resulting in the oil rich in the light component) and biodegradation (resulting in the oil rich in the heavy component and the decrease of the concentration of the component) during the migration, accumulation

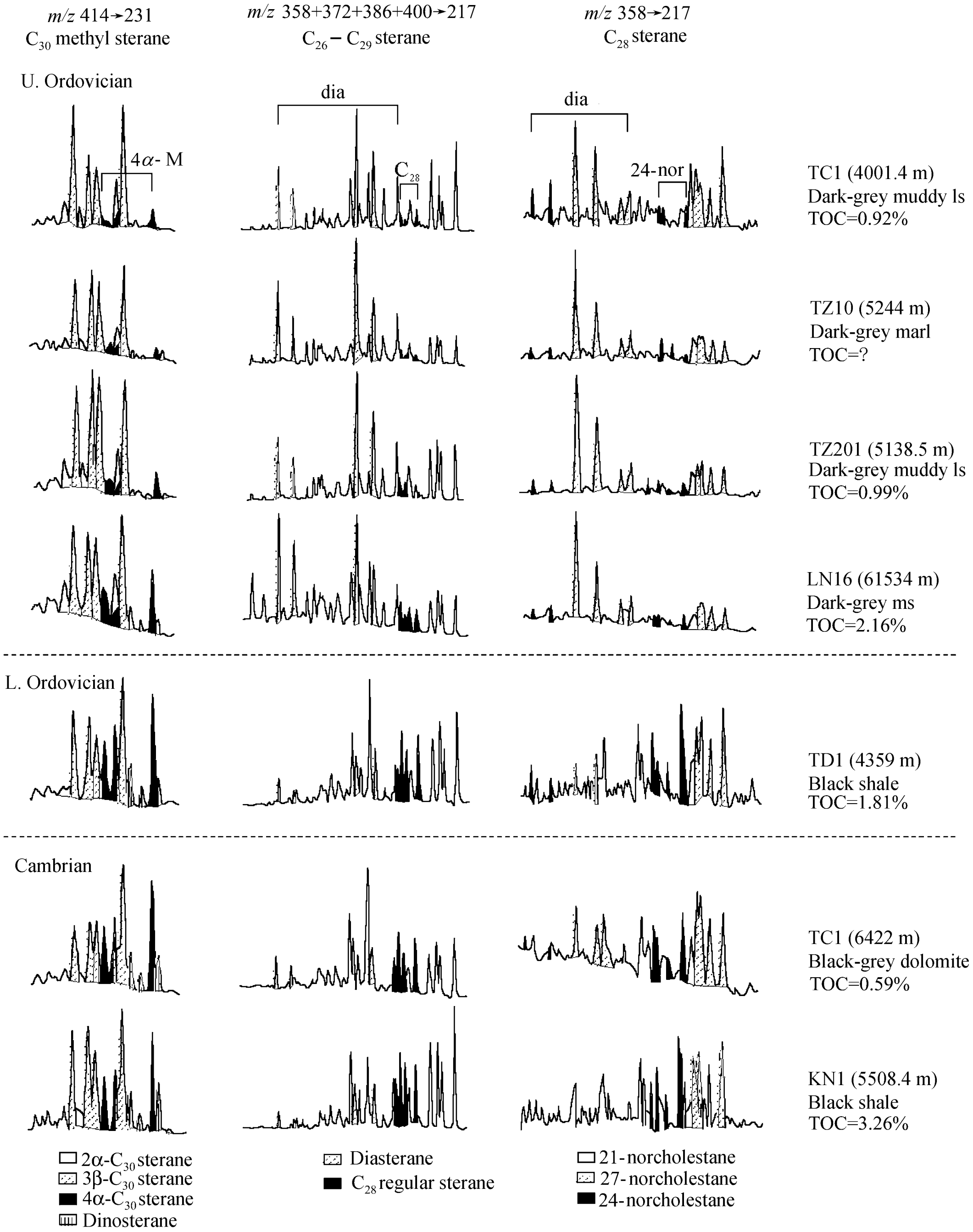

Fig. 1. The distribution of C_{30} methylsteranes (*m/z* 414→231), C_{27}—C_{29} steranes (*m/z* M^+→217) and C_{26} norcholestanes (*m/z* 358→217) in the extracts from Cambrian and Ordovician source rocks in the Tarim Basin, showing regular changes with the geologic age.

and adjustment. The parameters, composed of the compounds with obviously different molecular weights such as tricyclic terpane/hopane, C_{23} tricyclic terpane/C_{30} hopane, C_{24} tetracyclic terpane/C_{30} hopane, C_{19}—C_{21} tricyclic terpane/C_{23} — C_{24} tricyclic terpane and drimane/homodr- imane, have the biological origin to some extent. But comparisons among the data should have multiple meaning. Therefore, they should not be used for oil-source rock correlation in the Tarim Basin. Here we suggest that the algae-related steroid compounds with equal or near molecular weight and higher carbon number may be more suitable for marine oil-source rock correlations in the Tarim Basin. These compounds include dinosteranes derived from dinoflagellate, 4-methyl-24-ethylcholestanes and their aromatized steroids[6], 24-norcholestanes representing the records and behaviours of diatoms[7,8] and C_{28} steranes originated from diatom, coccolithophores and dinoflagellates[9]. As shown in fig. 1, it is clear that these parameters show an obvious difference in the extracts between the Cambrian and Ordovician. And from the point of thermodynamics, they are not affected by maturation or secondary alteration.

(1) Dinosteranes and 4α-methyl-24-ethylcholestanes.

Dinosteranes and 4α-methyl-24-ethylcholestanes are regarded as the dinoflagellate-specific biological markers[10,11], and dinoflagellate is known to originate from the Middle Triassic. Due to the identification of the abundance of dinosteranes and 4α-methyl-24-ethylcholestanes from the sediments which are rich in organic matter from the pre-Cambrian and Silurian, the origin of dinoflagellate may be much earlier than our imagination before[6,12]. As discussed above, there are obvious differences in the relative content of dinosteranes and 4α-methyl-24-ethylcholestanes in extracts from two sets of source rocks. All extracts from the Cambrian have relatively high dinosteranes content, whereas the extracts from the Middle-Upper Ordovician have a lower content of dinosteranes. This difference should be the foundation of the oil-source correlation. From the distribution of C_{30} methylsteranes from two groups of extracts and oils (fig. 2), it can be seen that the heavy oil from TD2 shows excellent similarity with the extract at intervals of 4674.2 m in the same well, with high abundance of dinosteranes and 4α-methyl-24-ethylcholestanes (fig. 2(a)). Whereas the oils from the Tabei uplift represented by the oils from LG9 (whether the heavy oils, or the normal oils, or condensates) show similarity with the extracts from the Upper Ordovician in TZ6, both with a low content of dinosteranes and 4α-methyl-24- ethylcholstanes and a high content of 3a-methyl-24-ethylcholestanes (fig. 2(b)).

From the relationship between the relative content of dinosteranes and 4α-methyl-24-ethylcholestanes in all extracts and oils (fig. 3(a)), it can be seen that there are distinct differences between the extracts from the Cambrian and most oils and the extracts from the Upper Ordovician. Except the oil from TD2, about 95% confidence interval of the Cambrian source rocks does not overlap those of other oils, which overlap with most Upper Ordovician extracts.

(2) Triaromatic dinosteranes and other triaromatized steroids. The mass chromatogram of triaromatic dinosterane (m/z 245) shows a consistent result with dinosteranes and 4α-methyl-24-ethylcholestanes. The oil from TD2 shows a good correlation with extracts from the Cambrian in the same well, with triaromatic dinosteranes (peak 7) as the most abundant compounds, 4-methyl-24-ethyltriaromatic cholestanes (peaks 8 and 11) as the second and 3β-methyl-24-ethyltriaromatic cholestane

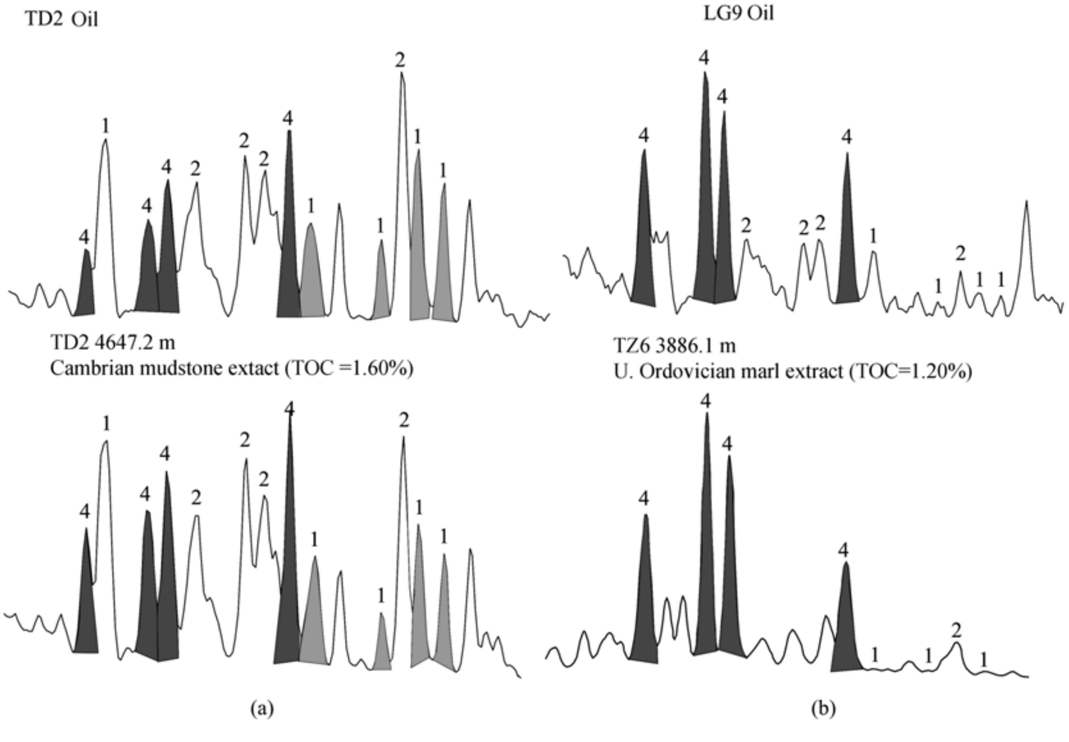

Fig. 2. The distribution of methylsteranes (m/z 231) in extracts and oils. (a) The heavy oil in TD2 and extract from interval of 4647.2 m, mudstone, Cambrian in TD2; (b) the heavy oil of LG9 and extract from interval of 3886.1 m, marls of Upper Ordovician from TZ6. Peak 1, 23,24-trimethylcholestanes (dinosteranes); peak 2, 4-methyl-24-ethylcholestane; peak 4, 3-methyl-24-ethylcholestanes.

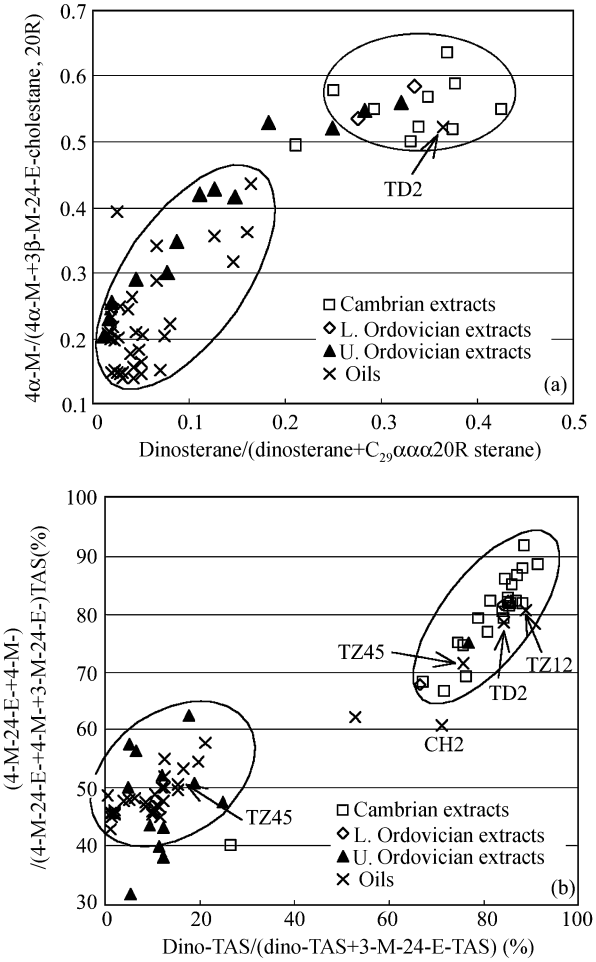

Fig. 3. Crossplot of dinosteranes/(dinosteranes+ααα20R C_{29} steranes) and 4α-methyl-24-ethylcholestanes/(4α + 3β)-methyl-24-ethylcholestanes (a) and crossplot of triaromatic dinosteranes/(triaromatic dinosteranes +3β-methyl-24-ethyltriaromatic cholestanes) and (4α-methyl-24-ethyl+4-methyl)/(4-methyl+4-methyl-24-ethyl +3-methyl-24-ethyl) triaromatic cholestanes ratios (b) in Tarim oils and rock extracts, showing clearly separation of the Cambrian and Upper Ordovician. Most marine oils overlap with the Upper Ordovician extracts. Dino-TAS: Triarmotic dinosteranes; 4-M-24-E-TAS: 4-methyl-24-ethyl triaromatic dinosteranes; 4-M-TAS: 4-methyl triaromatic dinosteranes; 3-M-24-E-TAS: 3-methyl-24-ethyl triaromatic dinosteranes.

(peak 9) as the least abundant compounds. The same to the oil from LG9 and extracts form the Middle-Upper Ordovician, which were characterized by 3β-methyl-24-ethyltriaromatic cholestane dominance, low concentration of other compounds and almost undetectable triaromatic dinosteranes, and compounds labeled "*" are supposed to be 2-methyl-24-ethylatriaromatic cholestanes (fig. 4(b), *m*/*z* 245).

From the crossplot of triaromatic dinosteranes (Dino-TAS)/(triaromatic dinosteranes+4α-methyl-24-ethyl triaromatic steranes (TAS)) and 4-methyl-24-ethyl triaromatic sternes/(4-methyl-24-ethyl-+3-methyl-24-ethyltriaromatic steranes) (fig. 3(b)), it can be seen that the ratios of Dino-TAS/(Dino-TAS+3β-methyl-24-ethyl TAS) and 4-methyl-24-ethyl TAS/(4-methyl-24-ethyl-+3-methyl-24-ethyl-)TAS in the extracts from the Cambrian and Lower Ordovician exceed 60%, while the two values in extracts of the Middle-Upper Ordovician are only 5%—25% and 30%—60%, respectively. The distinct differences of triaromatic dinosteranes and 4-methyl-24-ethyl-TAS between two sets of source rocks should be a very interesting case. Moldowan et al. thought that the abundance of triaromatic dinosteranes in the Paleozoic extracts might relate to the marine acritarch (phototrophs phytoplankton of uncertain affinity)[12], and the latter might originate from dinoflagellate which act as the primary production in Paleozoic oceans[3]. Bian's recent research suggested that the dinosteranes in the extracts from the Middle-Upper Cambrian could be an origin of *Paleogloeodinium* which should be widely spreaded in the Tarim ocean at that time[14]. The ultimate reason of the difference in the contents of dinosteranes in extracts from the Cambrian and Ordovician in the Tarim Basin is supposed to relate to the changing of paleo-oceanographic conditions between the Cambrian and the Ordovician time[5]. No matter what reason it is, this difference provides the additional proof for distinguishing the source rocks of the Cambrian and Ordovician. Most of the analyzed oils overlap with the area of the Upper Ordovician, except a few oils such as the heavy oil from TD2, oil from TZ45 (another oil from TZ45 overlapping with the Upper Ordovician), oil from TZ12 (a small amount of oil without commercial value produced in the sandy dolomite reservoir from the Lower Ordovician) and oil stain from CH2 (well Cao2 in Caohu Sag) overlapping with the Cambrian.

Analyzing the distribution of triaromatic steranes on the *m*/*z* 231 mass chromatogram, we found that there was also great difference between two group samples. The concentrations of peaks 24, 25 and 27 are rather high in extracts of the Cambrian and their corresponding oils, but very low in the extracts from the Middle-Upper Ordovician and their corresponding oils in LG9 which are dominated by peaks 26 and 28. Although the reason is not totally clear, these compounds used for oil-source rock correlation have the appied effect as other compounds as discussed above.

(3) 24-norcholestanes. 24-norchloesterols are known to be produced by eukaryotes. Whereas 21- and 27-norcholestanes seem to have no direct sterol precursors. Paleozoic and even older oils usually show little or no 24-norcholestanes[7,8,15]. Holba et al. found that 24-norcholestane and its derivatives appear most abundantly in the modern or Paleozoic diatomaceous sediment and oils generated from siliceous source rock, suggesting that diatoms are the direct or indirect origin of 24-norcholestane[7,8]. Since the earliest appearing of diatom was in the Jurassic and then it was flourishing in the

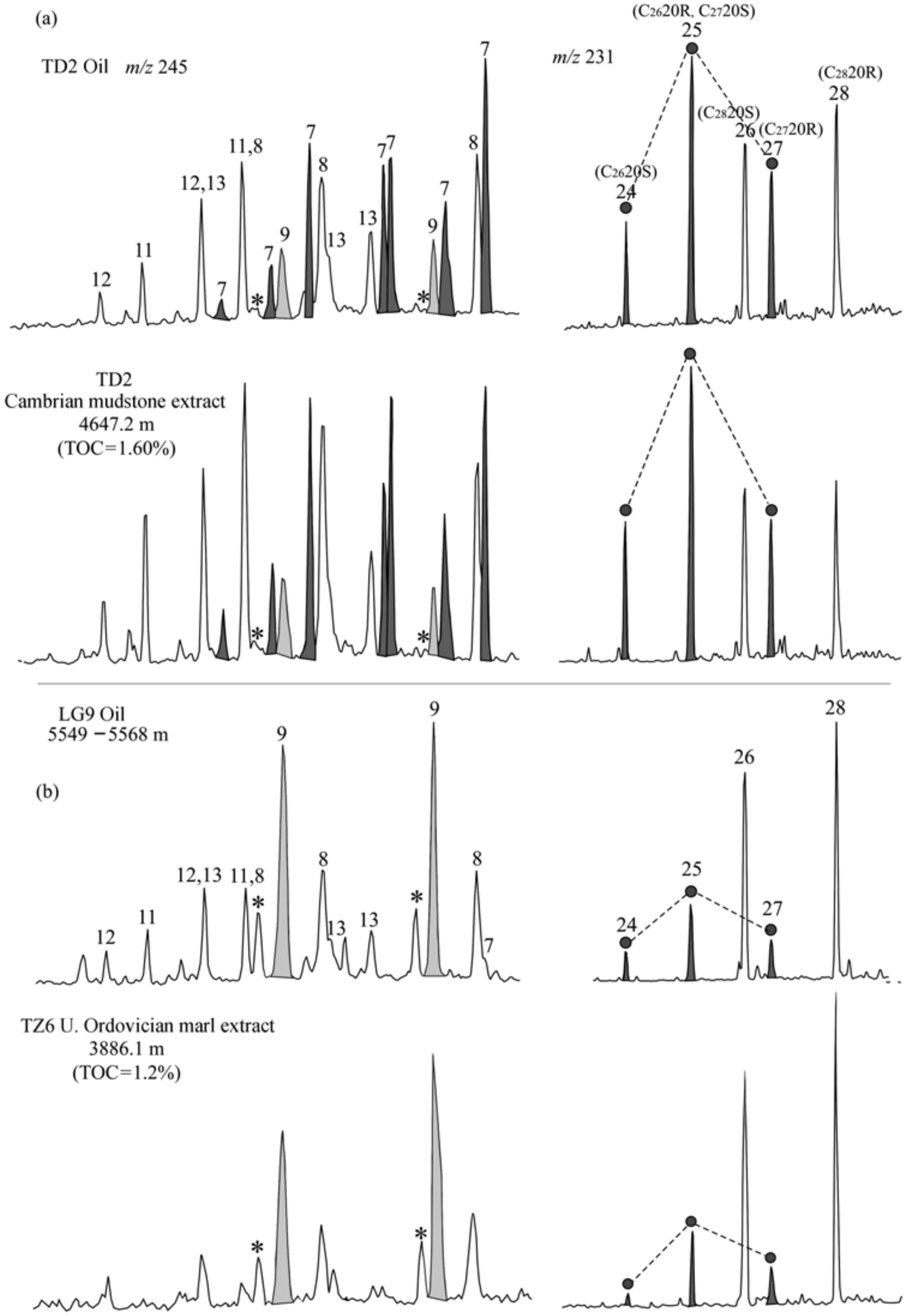

Fig. 4. The distribution of methyltriaromatic steranes (*m/z* 245) and triaromatic steranes (*m/z* 231) in Tarim oils and rock extracts. (a) Heavy oil from TD2 and extract of Cambrian mudstone from the depth of 4674.2 m in the same well; (b) heavy oil from LG9 and extract of Upper Ordovician muddy limestone from the depth of 3886.1 m in TZ6. Peak 7: 4,23,24-trimethyltriaromatic steranes (C_{29} triaromatic steranes); peak 8: 4-methyl-24-ethyltriaromatic steranes (C_{29}); peak 9: 3-methyl-24-ethyltriaromatic steranes; peak 11: 4-methyltriaromatic steranes (C_{27}); peak 12: 3-methyltriaromatic steranes (C_{27}); peak 13: 3-methyl-24-methyltriaromatic steranes (C_{28}).

Late Cretaceous[8], the ratios of 24-/27-norchloestane and 24-/27-nordiacholestane show two peak values in these two periods. But in the Tarim Basin, significant amounts of 24-norcholestane in all Cambrian rocks and some Ordovician rocks have been identified. The difference between the Cambrian to Lower Ordovician rocks and Upper Ordovician rocks is that the former is rich in 24-norcholestane, while the latter is rich in 27-cholestane (fig. 1). The 24-/27-norcholestane values of the Cambrian to Lower Ordovician extract are up to 0.3, while the values of Upper Ordovician extracts are less than 0.25 (fig. 5(a)). The crossplot of the 24-/27-norcholestane and triaromatic dinosteranes/(triaromatic dinosteranes +3β-methyl-24-ethyl-triaromatic dinosteranes) can be clearly separated into two sets of source rocks (fig. 5(a)). Most oils drop in the areas of Upper Ordovician extracts, and only a few oils such as TD2 drop in the areas of Cambrian extracts (fig. 5(a)).

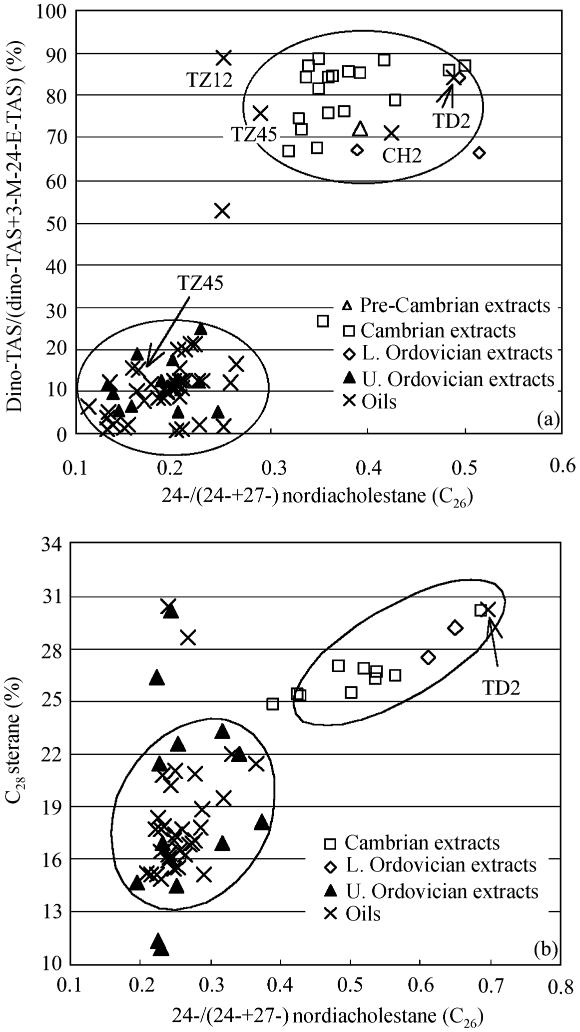

Fig. 5. Crossplot of 24-/27-norcholestanes and triaromatic dinosteranes/(triaromatic dinosteranes+3β-methyl-24-ethylcholestanes) and 24-/27-norcholestanes and C_{28} steranes, showing clear seperation of Cambrian and Upper Ordovician extracts. Most Tarim marine oils overlap with the Upper Ordovician extracts.

(4) C_{28} steranes. Studies of this kind of compound have shown that the increasing in C_{28} steranes among C_{27}—C_{29} steranes in the Jurassic and Cretaceous oils may be related to the increasing diversification of phytoplankton assemblages, including diatom, coccolithophores and dinoflagellates[9]. Interestingly, the Cambrian extracts have higher content of C_{28} steranes among C_{27}—C_{29} steranes (about 20%—26%), which are higher than the values of the early Paleozoic and even more ancient strata (3%—17%) reported by Grantham and Wakefield[9], and aslo higher than that of Middle-Upper Ordovician extracts. The C_{28} steranes distribution shows that most oils except oil in TD2 are located in the area of the Upper Ordovician, which is almost the same as the parameters mentioned above.

3 Discussion

As the result mentioned above, it will be reasonable that the ratios of dinosteranes/(dinostranes + 3β-methyl-24-ethylcholestanes), triaromatic dinosteranes/(triaromatic dinosteranes + 3β-methyl-24-ethyltriaromatic dinosteranes) and 24-/27-norcholestanes can be used as effective parameters for marine oil-source correlations in the Tarim Basin. Based on the correlations, we suggest that the discovered commercial reservoirs in Tazhong and Tabei uplifts at present mainly originate from the Upper Ordovician source rocks deposited in the slope of the marginal platform and the heavy oil from TD2 is a typical oil originated from Cambrian source rocks. In other words, if the heavy oil in TD2 is regarded as a type of oil having a close genetic origin with Cambrian, then the oils in Lunnan-Tahe-Hadexun oilfields and Tazhong area, whose molecular fossils are absolutely different from that of TD2, should be regarded as another type of oil, which means that their origin should be the Upper Ordovician only. However, some researchers proposed that most of the oil characterized by the molecular fossils of Upper Ordovician were the result of the pollution by the Middle-Upper Ordovician with lower maturity and abundant biomarkers during the oil migration. This leads to the oils generated from the Cambrian showing the Middle-Upper Ordovician character (Wang Tingdong et al., internal report). But this inference is lack of supporting experimental data.

Based on the quantification data of partial extracts and oils, it can be seen that the absolute concentration of terpanes and steranes in the extracts from the Middle-Upper Ordovician and Cambrian has not shown a consistent increasing or decreasing. The hopanes concentration in the extracts from the Middle-Upper Ordovician (6369.55 μg/g) is about 2.3 times higher than that in the Cambrian (2782.18 μg/g). Whereas the steranes concentration in the extracts from the Cambrian (2553.78 μg/g) is about 1.4 times higher than that in the Middle-Upper Ordovician (1834.44 μg/g). There is no such guestion that the concentrations in the extracts from the Middle-Upper Ordovician with medium maturity are always higher than those of the Cambrian with higher maturity. The difference should relate to various lithofacies. If the oils originated from Cambrian strata, firstly, they should have the Cambrian characteristics (rich in dinosteranes, 4-methylsteranes and their aromatized steriods and 24-norcholestanes), rather than the characteristics of the Middle-Upper Ordovician (poor in dinosteranes, 4-methylsteranes and their aromatized steriods and 24-norcholestanes). In fact, the distribution of many molecular fossils in crude oils resembles well with that of Middle-Upper Ordovician rocks and even no trace of the Cambrian could be found. On the other hand, because the abundance of steranes is not dominant in the extracts from the Middle-Upper Ordovician, oils polluted by the source rocks from the Middle-Upper Ordovician are unlikely to mask the bio-source of the Cambrian. Proportioning experiments in the lab suggested that if even only 25% Cambrian oil had been added to the oils originated from the Middle-Upper Ordovician, the source-specific information of the Cambrian could be clearly identified in this mixture. Thus, ascribing some specific characteristics of oil to the pollution by the Middle-Upper Ordovician apparently lacks persuasion.

Whether terpanes or steranes, their absolute concentrations in the oils (the concentration of hopanes and steranes in the normal oil are 463 and 537 μg/g respectively) are far lower than those in the extracts from Cambrian or Middle-Upper Ordovician rocks. This phenomenon is the result of the absorbing effect of the host media and the migration distance during the process of the expulsion and migration. Therefore, the biomarkers concentrations in the oils are only a small amount of concentrations in the extracts. The concentrations of oils and extracts are not in the same order of magnitude. So it should not be suitable to use the biomarkers concentrations for oil-source rocks correlation.

4 Conclusion

Depending on the correlation results above, two conclusions can be drawn. Firstly, the molecular fossils parameters selected here reflect the obvious differences between the extracts from the Cambrian-Lower Ordovician and Middle-Upper Ordovician. No matter what is the reason of the differences (biological and environmental, just like the discussion in ref. [4]), these differences formed the solid foundations of oil-source rock correlations. Secondly, the commercial oil reservoirs with various properties (whether heavy oils, normal black oils, condensates or waxy oils) discovered in Tabei and Tazhong uplifts at present have a close genetic relationship with Upper Ordovician source rocks deposited in the slope of the marginal plateform. More importantly, we have discovered the oil in TD2, a typical oil generated from Cambrian source rocks. This discovery not only proves the existence of two source oils in the Tarim Basin thus expanding the exploration scope, but aslo verifies the effectiveness of the chosen parameters for distinguishing two sets of source rocks and their corresponding oils from the research point.

Acknowledgements Partial biomarkers analysis and quantification was finished in the Molecular Organic Geochemistry Laboratory of Standford University. Guidance and assistance were provided by Prof. J. M. Moldowan and Dr. A. D. Hanson. Reviews by Prof. Wang Tieguan and Prof. Wang Peirong greatly improved this article. This work was supported by the National Key Programs of Science and Technology of China ——“Petroleum and Natural Gas Exploration in the Tarim Basin” during the 9th Five-Year Plan and the Standford China Industrial Affiliates.

References

1. Ourisson, G., Albrecht, P., Rohmer, M., The microbial origin of fossil fuels, Scientific American, 1984, 251: 44.
2. Petrers, K. E., Moldowan, J. M., The biomarker guide, Interpreting Molecular Fossils in Petroleum and Ancient Sediments (ed. Cliffs, E.), New Jersey: Prentice Hall, 1993, 230—232.
3. Moldowan, J. M., Trails of life, Chemistry in Britain, 2000, 36: 34.
4. 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, 2002, 45(3): 193.
5. Zhang, S. C., Hanson, A. D., Moldowan, J. M. et al., Paleozoic oil-source rock correlations in the Tarim Basin, NW China, Organic Geochemistry, 2000, 31: 273.
6. Moldowan, J. M., Dahl, J., Jacobson, S. R. et al., Chemostratigraphic reconstructuion of biofacies: Molecular evidence linking Cyst-forming dinoflagellates with pre-Triassic ancestors, Geology, 1996, 24(2): 159.
7. Holba, A. G., Tegelaar, E. W., Huizinga, B. J. et al., 24-norcholestanes as age-sensitive molecular fossils, Geology, 1998a, 26: 783.
8. Holba, A. G., Dzou, L. I. P., Masterson, W. D. et al., Application of 24-norcholestanes for constraining the age petroleum, Organic Geochemistry, 1998b, 29: 1269.
9. Grantham, P. J., Wakefield, L. L., Variations in the sterane carbon number distributions of marine source rock derived crude oils through geological time, Organic Geochemistry, 1988, 12: 61.
10. Volkman, J. K., Barrett, S. M., Dunstan, G. A. et al., A new source of 4-methyl sterols and 5α(H)-stanols in sediments: Prymnesiophyte microalgae of the genus Pavlova, Organic Geochemistry, 1990, 15: 489.
11. Withers, N., Dinoflagellate sterols, The Biology of Dinoflagelltes (ed. Taylor, F. J. R.), Oxford: Blackwell Scientific, 1987, 316.
12. Moldowan, J. M., Talyzina, N. M., Biogeochemical evidence for dinoflagellate ancestors in the early Cambrian, Science, 1998, 281: 1168.
13. Tasch, P., Paleobiology of the Invertebrates: Data Retrieval from the Fossil Record, New York: Wiley & Sons, 1980.
14. Bian Lizeng, Zhang Shuichang, Zhang Baoming et al., A kind of coccoid dinoflagellates-like fossils gives a new exploration of source of dinosterane in the Early-Middle Cambrian, Chinese Science Bulletin, 2001, 46 (5), 420.
15. Moldowan, J. M., Lee. C. Y., Watt, D. C. et al., Analysis and occurrence of C_{26}-sterane in petroleum and source rocks, Geochimica et Cosmochimica Acta, 1991, 55: 1065.

(Received August 12, 2002)