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Mesozoic non-marine petroleum source rocks determined by palynomorphs in the Tarim Basin, Xinjiang, northwestern China

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Abstract – The Tarim Basin in Northwest China hosts petroleum reservoirs of Cambrian, Ordovician, Carboniferous, Triassic, Jurassic, Cretaceous and Tertiary ages. The sedimentary thickness in the basin reaches about 15 km and with an area of 560 000 km^2, the basin is expected to contain giant oil and gas fields. It is therefore important to determine the ages and depositional environments of the petroleum source rocks. For prospective evaluation and exploration of petroleum, palynological investigations were carried out on 38 crude oil samples collected from 22 petroleum reservoirs in the Tarim Basin and on additionally 56 potential source rock samples from the same basin. In total, 173 species of spores and pollen referred to 80 genera, and 27 species of algae and fungi referred to 16 genera were identified from the non-marine Mesozoic sources. By correlating the palynormorph assemblages in the crude oil samples with those in the potential source rocks, the Triassic and Jurassic petroleum source rocks were identified. Furthermore, the palynofloras in the petroleum provide evidence for interpretation of the depositional environments of the petroleum source rocks. The affinity of the miospores indicates that the petroleum source rocks were formed in swamps in brackish to lacustrine depositional environments under warm and humid climatic conditions. The palynomorphs in the crude oils provide further information about passage and route of petroleum migration, which is significant for interpreting petroleum migration mechanisms. Additionally, the thermal alternation index (TAI) based on miospores indicates that the Triassic and Jurassic deposits in the Tarim Basin are mature petroleum source rocks.

Keywords: spores and pollen, petroleum source rocks, petroleum migration, oil field, Triassic–Jurassic, Tarim Basin.

1. Introduction

Petroleum and source rock correlation is a classic tool for source rock identification. Geochemists use chemical biomarkers as indicators to correlate petroleum and source rocks. Palynomorphs can also be used as indicators for petroleum and source rock correlation, because the walls of spores and pollen are resistant to the thermal alteration in the process of petroleum genesis, as well as to the effects of petroleum migration. Moreover, palynomorphs can indicate the geological age and sedimentary environments of source rocks. Consequently, palynology is a useful scientific method in petroleum source research, especially in non-marine sediments.

There are several publications dealing with the identification of oil source rocks. The first was by Sanders (1937), who extracted spores, algae and fungi from Cretaceous and Tertiary crude oil samples from Mexico, and Tertiary crude oil samples from Romania. Waldschmidt (1941) extracted diatom and plant fragments from Permian crude oils of Colorado, USA. Timofeev & Karimov (1953) made palynological investigations on crude oils of Russia. De Jersey (1965) reported plant microfossils in crude oils of the Moonie oil field in Queensland, Australia. On the other hand, Hunt (1979) documented that spores and pollen are too large to migrate along with liquid hydrocarbons, and he considered palynomorphs in petroleum to be *in situ*, deriving from the reservoir rocks themselves. However, Jiang & Yang (1980) described Cretaceous spores and pollen from crude oils in Tertiary reservoirs and in Silurian metamorphic rocks of the Yumen oil field in the Jiuxi Basin, China. The presence of spores and pollen in the crude oils indicates that these can migrate along with petroleum. Hua & Lin (1989) suggested that microfissures resulting from abnormal pressures occurring in source rocks should constitute the important pathways of petroleum primary migration in the Jiuxi Basin. In addition, Jiang (1990, 1996) found Carboniferous and Permian miospores in crude oils from an igneous rock reservoir of the Junggar Basin, China. The discovery of these spores and pollen in the igneous reservoir may serve as a direct

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indication that they were expelled from source rocks and migrated along with petroleum into the reservoir. McGregor (1996) reviewed studies of palynomorphs in petroleum and considered that these studies merit wider attention, because the results and interpretations of researchers working on this subject have achieved credibility.

The Tarim Basin of Xinjiang, northwest China, is a continental petroliferous basin where some prospective large oil–gas fields have been found. Graham *et al.* (1990) reported analyses of potential petroleum source rocks of the Xinjiang basins, and suggested that the Upper Triassic to Middle Jurassic sequences which were sufficiently buried comprise a potentially significant oil source in the northern Tarim Basin. Hendrix *et al.* (1995) provided a detailed organic geochemical database for organic-rich Lower and Middle Jurassic strata throughout central Xinjiang. They presented field and laboratory evidence demonstrating that organic-rich Lower and Middle Jurassic strata are dominated by terrestrial-derived type III kerogens, and concluded that Jurassic coaly strata have significant potential as petroleum source rocks in the northern Tarim, southern Junggar and Turpan basins. Hanson *et al.* (2000) conducted organic geochemical analyses on a large suite of oils and source rocks extracted from the Tarim Basin. On the basis of statistical cluster analysis, they suggested that most of the oils originated from source rocks deposited in either the Middle–Upper Ordovician or the Upper Triassic to Lower–Middle Jurassic. Based on previous preliminary studies of spores and pollen in crude oils from several petroliferous provinces in the Tarim Basin, Jiang & Yang (1983, 1986, 1992, 1996, 1999) suggested that the Triassic and Jurassic systems should contain favourable petroleum source rocks. This paper addresses a further method of correlation between petroleum and source rocks with palynomorphs from the non-marine Mesozoic deposits, presents analysis of additional material, and discusses the depositional environments of the petroleum source rocks as well as mechanisms of petroleum migration in the Tarim basin.

2. Geological background

The Tarim Basin in the Xinjiang Uygur Autonomous Region of Northwestern China lies between 36 and 42° N latitude, and 74 and 90° E longitude (Fig. 1). The basin is bounded to the north by the Tianshan Mountain Range, to the southwest by the Kunlun Mountain Range, and to the southeast by the Altun Mountain Range. It is a large cratonic basin with a superimposed sedimentary thickness of 13 to 15 km. The Hercynian orogeny of Carboniferous to Permian age resulted in uplift of the Tianshan fold belt and the Kunlun fold belt, as well as evolution of the non-marine sedimentary basin (Zhou & Zheng, 1990).

Mesozoic strata of the Tarim Basin are non-marine, with the exception of Upper Cretaceous shallow-marine strata in the western basin (Zhou & Chen, 1990; Zhou, 2001) (Fig. 2). During Triassic times, lacustrine sedimentary sequences developed in the Kuqa and the North Tarim depressions. The Lower Triassic Ehuobulake Formation consists primarily of greyish brown sandstones and conglomerates intercalated with greyish green and dark grey mudstones, with a total thickness reaching 548 to 592 m. The Middle Triassic Karamay Formation is mainly composed of dark grey, greenish grey and black mudstones and grey siltstones intercalated with greyish brown sandstones with a thickness of 424 to 572 m. The lower Upper Triassic Huangshanjie Formation consists of dark grey mudstones and black carbonaceous mudstones intercalated with greyish green fine-grained sandstones, grey argillo-calcareous rocks and coals; the thickness is 135 to 413 m. The uppermost Triassic Taliqike Formation includes grey sandstones, dark grey and greenish grey mudstones, grey argillo-calcareous rocks, black carbonaceous mudstones and coal beds with a thickness of 545 m to 836 m.

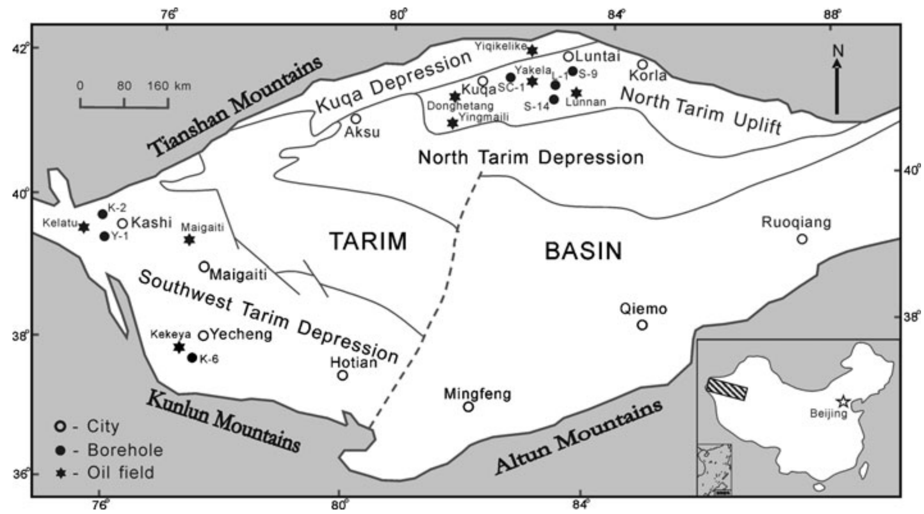

Figure 1. Sketch map showing tectonic subdivisions, and locations of oil fields and boreholes in the Tarim Basin, northwestern China.

Age	Epoch Symbol	Thickness (m)	Reservoirs	Oil fields	Formations (Fm.)/ Groups (Gr.)	Sedimentary facies
Tertiary	N		▲	Kelatu Kekeya		
	E		▲	Yingmaili		
Cretaceous	K_2	450	▲		Yengisar Gr.	Shallow-marine and lagoon facies
	K_1	300–1500			Kapushaliang (Kizilsu) Gr.	
Jurassic	J_3	256–278	▲	Yiqikelike Yakela	Qigu (Kuzigongsu) Fm.	Terrestrial clastic deposits
	J_2	872–1245	▲		Qiakemake (Taerga) Fm. ◆ Kezilenuer (Yangye) Fm. ◆	Lacustrine and swampy facies Meandering fluvial facies (Kuqa, North Tarim, Southwest Tarim depressions)
	J_1	523–1160	▲		Yangxia (Kangsu) Fm. ◆ Ahe(Shalitashi) Fm.	
Triassic	T_3	545–836	▲	Yakela Lunnan	Taliqike Fm. ◆	Braided fulvial facies Lacustrine facies (Kuqa and North Tarim depressions)
		135–413	▲		Huangshanjie Fm. ◆	
	T_2	424–572	▲		Karamay Fm. ◆	
	T_1	548–592	▲		Ehuobulake Fm. ◆	
Ordovician	O_{2+3}	792	▲	Lunnan		
	O_1	808	▲	Yakela		

Abbreviations: O_1-Lower Ordovician; O_{2+3}-Middle and Upper Ordovician; T_1-Lower Triassic; T_2-Middle Triassic; T_3-Upper Triassic; J_1-Lower Jurassic; J_2-Middle Jurassic; J_3-Upper Jurassic; K_1-Lower Cretaceous; K_2-Upper Cretaceous; E-Eocene; N-Neogene; ▲-Oil reservoir; ◆-Principal petroleum source.

Figure 2. A brief stratigraphic framework showing principal reservoirs, oil fields, major petroleum source rocks and their sedimentary facies in the Tarim Basin, Xinjiang, China.

The Ehobulake, Karamay, Huangshanjie and Taliqike formations contain various kinds of fossils, including plants, miospores, megaspores, acritarchs, charophytes and conchostracans (Zhou & Chen, 1990; Liu, 2003). The Upper Triassic dark grey and black organic-rich mudstones probably represent lacustrine deposits (Ma & Wen, 1991). In addition, an Upper Triassic braided fluvial facies was reported in the north Tarim basin (Hendrix *et al.* 1992) (Fig. 2).

During the Jurassic period, the lacustrine area further expanded, and both lacustrine and swampy sequences are well developed in the Kuqa Depression, the North Tarim Depression and the Southwest Tarim Depression. The Lower Jurassic Ahe (Shalitashi) and Yangxia (Kangsu) formations consist mainly of grey sandstones and dark grey mudstones intercalated with black carbonaceous mudstones and coals containing plants, miospores, megaspores and acritarchs (Liu, 2003); the thickness varies from 523 to 1160 m. The Middle Jurassic Kezilenuer (Yangye) and Qiakemake (Taerga) formations include grey sandstones, dark grey and greenish grey mudstones, black carbonaceous mudstones, coal beds and oil shales containing miospores, megaspores, estherids, ostracods and bivalves; the thickness ranges from 872 to 1245 m (Liu, 2003). Most Lower and Middle Jurassic strata in the basin consist of interbedded sandstone, siltstones, shales and coals, and were interpreted as meandering fluvial facies by Hendrix *et al.* (1995). The Upper Jurassic Qigu Formation consists of brown and brownish red mudstones intercalated with sandstones, and contains charophytes and bivalves, and the thickness is 256 to 278 m (Ma & Wen, 1991) (Fig. 2).

The Lower Cretaceous Kapushaliang (Kizilsu) Group in the Tarim Basin consists of brownish red sandstone and conglomerate intercalated with greyish green siltstones and mudstones, containing ostracods, estherids, charophytes and miospores; the thickness is about 300 to 1500 m (Jiang, He & Dong, 1988; Ma & Wen, 1991; Li, 2000; Jiang *et al.* 2006, 2007). The Upper Cretaceous Yengisar Group in the western basin, dominated by shallow-marine, littoral and lagoonal deposits, and with a thickness of 450 m, carries a rich marine fauna of Tethyan forms (Huang & Chen, 1987;

Ma & Wen, 1991). In addition, dinoflagellate cysts and acritarchs from the Yengisar Group were reported in Xinjiang (Yu & Zhang 1980) (Fig. 2).

It is noteworthy that tectonism in the Tarim Basin created four depressions, three uplifts, several stratigraphic angular unconformities, and many structural traps and faults (Zhou & Zheng, 1990). The depressions are favourable for preservation of organic material and formation of petroleum; the uplifts provide favourable traps for accumulation of petroleum. Unconformable contacts and faults can act as available passages for migration of petroleum. Structural traps within a depression or within an uplift between two depressions are usually the targets of petroleum migration. In fact, commercial oil and gas fields have been found in the Kuqa Depression, the Southwest Tarim Depression, and the North Tarim Uplift located between the Kuqa Depression and the North Tarim Depression (Fig. 1). These depressions can provide sufficient petroleum sources for large oil and gas fields.

3. Material and methods

Thirty-eight crude oil samples collected from 22 petroleum reservoirs in seven oil fields in the Tarim Basin were investigated in our study. These oilfields include the Yiqikelike, Yakela, Lunnan, Yingmaili, Kelatu, Maigaiti and Kekeya oil fields (Fig. 1). In addition, 32 rock samples collected from Triassic and Jurassic strata that crop out near Kuqa, Aksu and Kashi, and 24 core samples collected from the boreholes SC-1, S-9, S-14, K-2 and K-6 in the basin (Fig. 1), were used for correlation between petroleum and source rocks.

The method described by Jiang (1990) for extraction of spores and pollen from crude oil samples was adopted in this study to extract palynomorphs, including spores, pollen, algae and fungi from the petroleum. More than five litres of crude oil were used for each sample. The procedure of this method includes oil sample dilution with benzene or gasoline, oil sample filtration in a heater (70–75 °C), insoluble organic matter (kerogen) extraction in a Soxhlet apparatus using benzene ether, ketone and alcohol, and fossil concentration by heavy liquid flotation. The rock samples, including those from outcrops and cores, were prepared by standard methods using 10 % hydrochloric acid, 40 % hydrofluoric acid and 5 % potassium hydroxide. Gravity separation with a cadmium iodide–potassium iodide solution ($CdI:KI:H_2O = 10:9:9$) was used to concentrate palynomorphs from rocks. All the miospore fossils were mounted in glycerin jelly for study by light microscopy.

Assuming the palynomorphs found in the crude oils and in the rocks have been correctly identified, the palynomorphs recovered from the oils are used to determine the geological age of the rock that provided the sources of the oil. Correlations between palynomorphs in oils and those in rocks have been applied to determine geological ages and stratohorizons of petroleum source rocks. Thermal alteration index (TAI) based on spore/pollen colour was used to judge the maturity of petroleum source rocks (Traverse, 1988).

4. Palynomorphs in the Tarim Basin crude oils

In the Tarim Basin, a total of 173 species of spores and pollen referred to 80 genera, and 27 species of algae and fungi referred to 16 genera, were identified. Most of the palynomorphs in crude oils are Triassic and Jurassic species (Figs 3, 4), and the rest are time-transitional palynomorphs.

4.a. Triassic palynomorphs

Our investigation demonstrates that Triassic palynomorphs are found in crude oils from every petroleum reservoir in the North Tarim Uplift. Sixty species of Triassic spores and pollen are identified in crude oils from the Ordovician, the Triassic and the Jurassic reservoirs of the Yakela oil field and the Lunnan oil field, as well as in the Cretaceous reservoir of the Yakela oil field in the North Tarim Uplift. It is noted that these miospores have previously been reported from the Keuper stage, or upper Triassic Rhaetion stage, or the Triassic in Europe, Australia and in Xinjiang, Shanxi and Yunnan provinces of China (Table 1).

4.b. Jurassic palynomorphs

Jurassic palynomorphs are found in crude oils from the different petroleum reservoirs in the North Tarim Uplift, the Kuqa Depression and the Southwest Tarim Depression. Sixty-two species of Jurassic spores and pollen are found in crude oils from the Ordovician, Triassic, Jurassic, Cretaceous and Palaeogene reservoirs in the north Tarim, and Neogene reservoirs in the Southwest Tarim. These miospores are widely distributed in the Jurassic strata of Eurasia, North America and Australia (Table 2). Some of them were initially documented from the Lower to Middle Jurassic deposits covering different regions; others have been recorded ranging through the Jurassic sequences.

In addition, some fossil fungi, algae and acritarchs are found in crude oils from the Yakela oil field in the North Tarim, and from the Kekeya oil field and the Maigaiti oil field in the Southwest Tarim (Table 3). They are significant for indicating sedimentary environments of the petroleum source rocks.

5. Identification of petroleum source rocks in the Tarim Basin

The miospores extracted from crude oils usually form a three-part assemblage that represents the source bed, carrier bed and reservoir bed, each of which is different in geological age. The reservoir rocks of an oil field are always known, so spores and pollen deriving from the reservoir bed itself can be easily separated

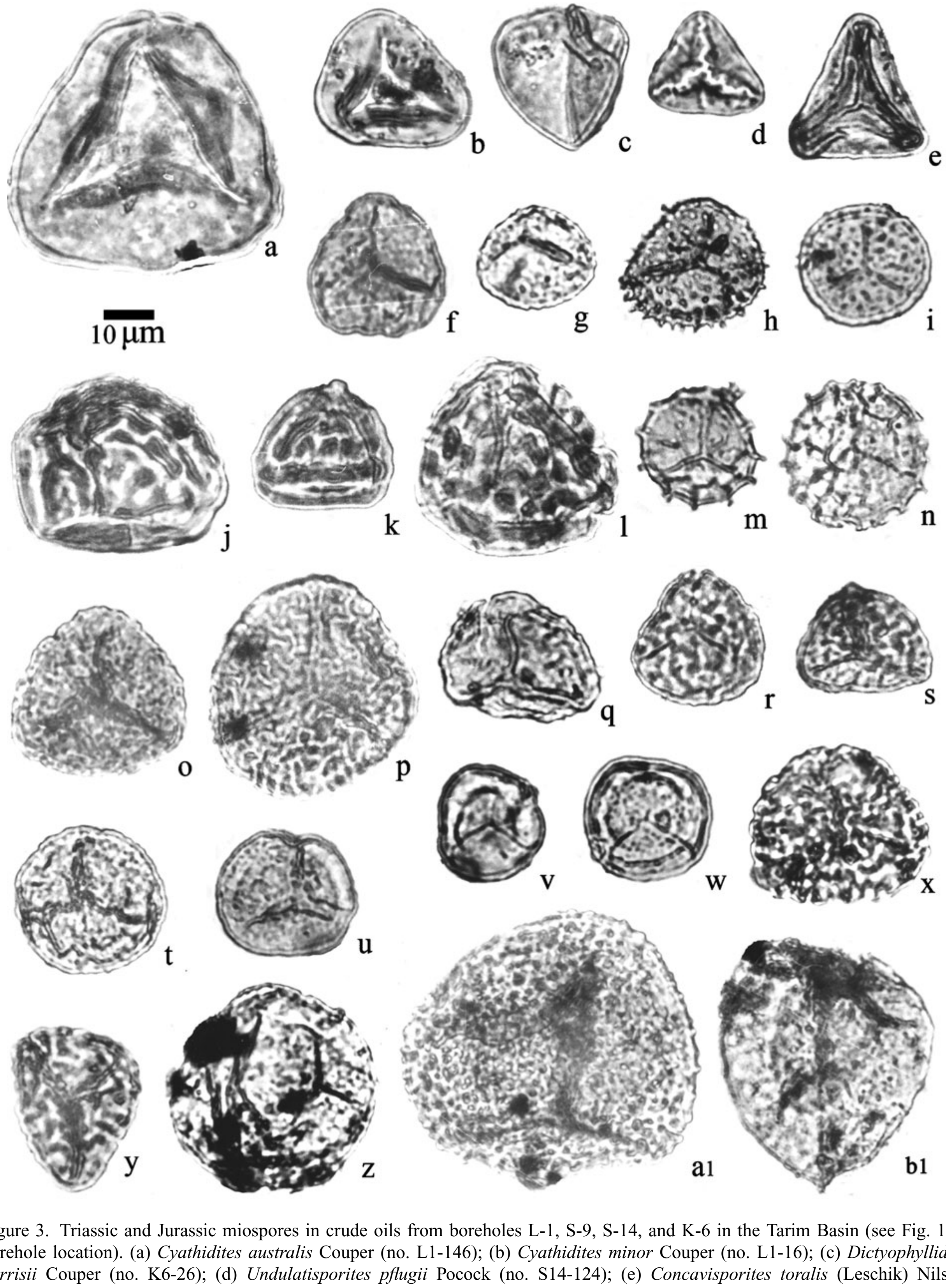

Figure 3. Triassic and Jurassic miospores in crude oils from boreholes L-1, S-9, S-14, and K-6 in the Tarim Basin (see Fig. 1 for borehole location). (a) *Cyathidites australis* Couper (no. L1-146); (b) *Cyathidites minor* Couper (no. L1-16); (c) *Dictyophyllidites harrisii* Couper (no. K6-26); (d) *Undulatisporites pflugii* Pocock (no. S14-124); (e) *Concavisporites toralis* (Leschik) Nilsson (no. L1-4); (f) *Granulatisporites jurassicus* Pocock (no. L1-26); (g) *Apiculatisporis parvispinosus* (Leschik) Qu (no. S14-168); (h, i) *Apiculatisporis spiniger* (Leschik) Qu (h, no. L1-6: i, no. S14-80); (j) *Duplexisporites amplectiformis* (Kara-Murza) Playford & Dettmann (no. L1-23); (k) *Duplexisporites anagrammensis* (Kara-Murza) Playford & Dettmann (no. L1-169); (l) *Duplexisporites scanicus* (Nilsson) Playford & Dettmann (no. L1-1); (m) *Lycopodiumsporites subrotundum* (Kara-Murza) Pocock (no. L1-92); (n) *Lycopodiumsporites paniculatoides* Tralau (no. L1-105); (o) *Lycopodiacidites rhaeticus* Schulz (no. S9-21); (p, q) *Lycopodiacidites kuepperi* Klaus (p, no. S14-50; q, no. S14-40); (r, s) *Lophotriletes corrugatus* Ouyang & Li (r, no. L1-29; s, no. L1-1); (t) *Retusotriletes mesozoicus* Klaus (no. S9-32); (u) *Lundbladispora subornata* Ouyang & Li (no. S9-22); (v) *Limatulasporites parvus* Qu & Wang (no. S14-103); (w) *Limatulasporites dalongkouensis* Qu & Wang (no. S14-64); (x) *Tigrisporites halleinis* Klaus (no. S14-101); (y) *Zebrasporites kahleri* Klaus (no. S14-53); (z) *Verrucosisporites contactus* Clarke (no. S14-40); (a1) *Verrucosisporites remyanus* Madler (no. L1-111); (b1) *Aratrisporites fischeri* (Klaus) Playford & Dettmann (no. L1-1).

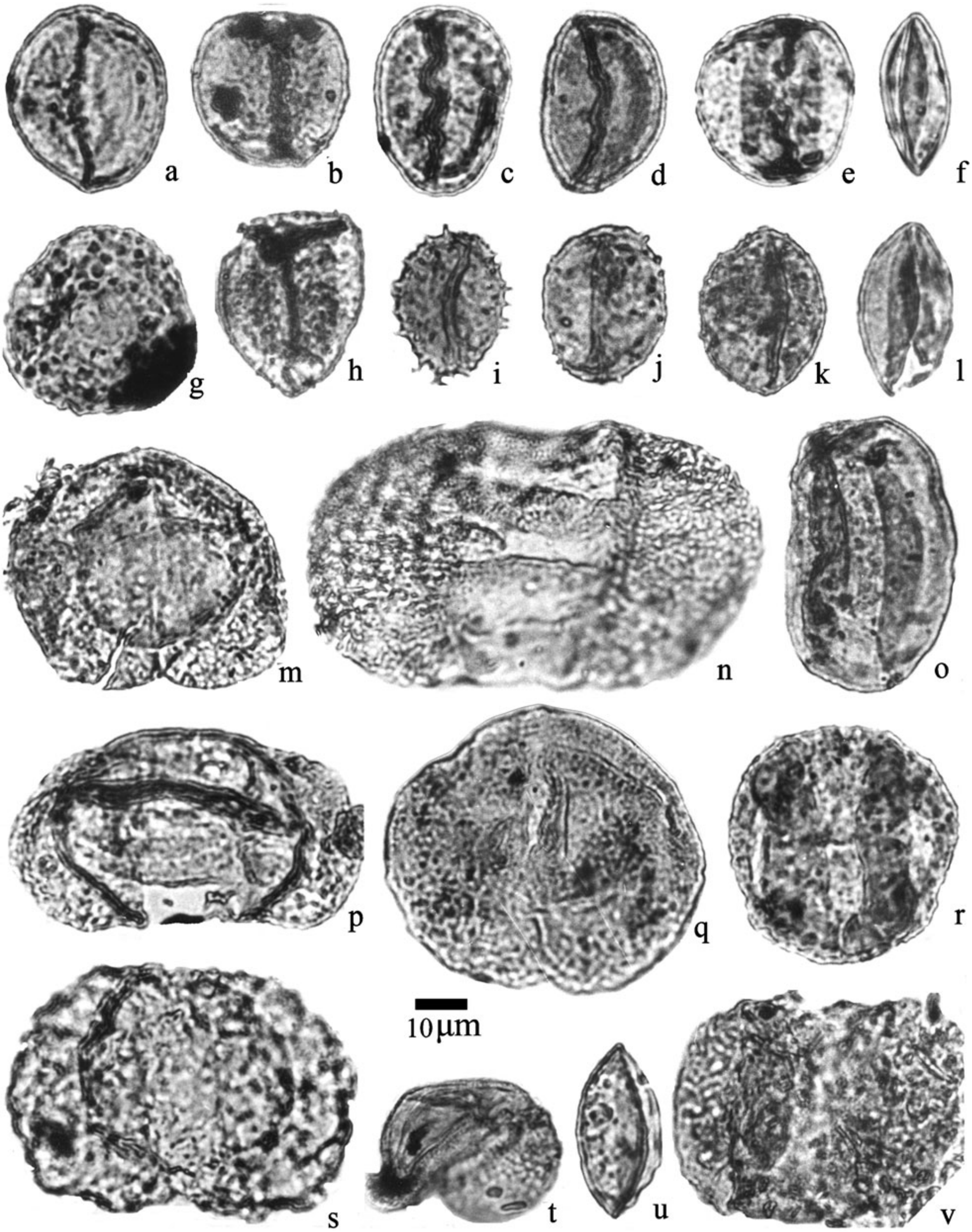

Figure 4. Triassic and Jurassic miospores in crude oils from Boreholes L-1, S-9, S-14, K-2, K-6 and Y-1 in the Tarim Basin (see Fig. 1 for borehole location). (a) *Aratrisporites scabratus* Klaus (no. S14-61); (b) *Aratrisporites paenulatus* Playford & Dettmann (no. L1-1); (c, d) *Aratrisporites granulatus* (Klaus) Playford & Dettmann (c, no. S14-119; d, no. S14-46); (e) *Aratrisporites strigosus* Playford (no. S14-144); (f) *Cycadopites typicus* (Mal.) Pocock (no. S14-134); (g) *Cerebropollenites carlylensis* Pocock (no. Y1-11); (h) *Aratrisporites fischeri* (Klaus) Playford & Dettman (no. L1-165); (i) *Aratrisporites tenuispinosus* Playford (no. L1-41); (j, k) *Aratrisporites parvispinosus* Leschik (j, no. L1-92; k, no. L1-191); (l) *Cycadopites nitidus* (Balme) Pocock (no. S14-3); (m) *Chordasporites orientalis* Ouyang & Li (no. L1-50); (n) *Taeniaesporites pellucidus* (Goubin) Balme (no. S9-9); (o) *Bennettiteaepollenites lucifer* (Thierg.) Potonié (no. L1-20); (p) *Chordasporites singulichorda* Klaus (no. S14-58); (q) *Piceites pseudorotundiformis* (Mal.) Pocock (no. L1-15); (r) *Quadraeculina limbata* Maljavkina (no. Y1-9); (s) *Protopinus scanicus* Nilsson (no. Y1-34); (t) *Cedripites minor* Pocock (no. K6-10); (u) *Cycadopites subgranulosus* (Couper) Clarke (no. S14-131); (v) *Podocarpidites florinii* Pocock (no. K2-4).

Table 1. Triassic spores and pollen in crude oils from reservoirs of different ages in the Tarim Basin and their distribution in the Triassic strata of Europe, Asia and Australia

	Regions				GB	DE	CH	AT	RO	CN	AU
	References				[1]	[2]	[3]	[4]	[5]	[6]	[7]
	Count of specimens in reservoirs										
Spores and pollen	O	T	J	K	T_3	T	T_3	T_3	T	T	T
Spores											
Apiculatisporis globosus (Leschik) Playford & Dettmann 1965	4	6	2				*			–	–
A. parvispinosus (Leschik) Qu 1980	5	6	4				*			–	
A. spiniger (Leschik) Qu 1980	6	9	3	1			*			–	
Aratrisporites coryliseminis Klaus 1960	6	4	2					*		–	
A. fischeri (Klaus) Playford & Dettman 1965	5	8						*		–	–
A. granulatus (Klaus) Playford & Dettman 1965	9	7	4	3				*		–	–
A. paenulatus Playford & Dettmann 1965	4	4								–	*
A. paraspinosus Klaus 1960		3						*		–	
A. parvispinosus Leschik 1955	2	5					*			–	
A. scabratus Klaus 1960	7	9	4	2				*		–	
A. strigosus Playford 1965	8	14	3	3						–	*
A. tenuispinosus Playford 1965		5								–	*
Asseretospora gyrata (Playf. & Dettm.) Schuurman 1977	3	8	3	2						–	*
Calamospora nathorstii (Halle) Klaus 1960	7	5	4	2	*			–		–	
C. tener (Leschik) Mädler 1964	3	6	2	1		–	*			–	
Camarozonosporites rudis (Leschik) Klaus 1960		7					*	–		–	
Conbaculatisporites mesozoicus Klaus 1960	3							*		–	
Limatulasporites dalongkouensis Qu & Wang 1986	6	8	3							*	
L. parvus Qu & Wang 1986	9	11	4	2						*	
Lophotriletes corrugatus Ouyang & Li 1980		5								*	
Lundbladispora nejburgii Schulz 1964	3	5	2			*			–	–	
L. playfordi Balme 1963		3								–	*
L. plicata Bai 1983	2	4								*	
L. subornata Ouyang & Li 1980	3	7	2							*	
Lycopodiacidites kuepperi Klaus 1960	7	4	2	1				*		–	
L. rhaeticus Schulz 1967	2	5	2	2		*				–	
Multinodisporites junctus Ouyang & Li 1980		3	1							*	
Osmundacidites alpinus Klaus 1960	4	6	5	2				*		–	
Punctatisporites ambiguus Leschik 1955	3	4					*			–	
P. microtumulosus Playford & Dettmann 1965	4	4								–	*
P. triassicus Schulz 1964	12	15	4	3		*			–	–	
Retusotriletes arcticus Qu & Wang 1986		6	2	1						*	
R. mesozoicus Klaus 1960	5	4	3	3				*		–	
Tigrisporites halleinis Klaus 1960	5							*		–	
Verrucosisporites contactus Clarke 1965	7				*					–	
V. remyanus Mädler 1964		5				*				–	
Zebrasporites kahleri Klaus 1960	5							*		–	
Pollen											
Alisporites aequalis Mädler 1964		4				*				–	
A.australis de Jersey 1962	3	3	4							–	*
A. fusiformis Ouyang & Li 1980		4								*	
A. parvus de Jersey 1962	3	5	5	3						–	*
Cedripites parvisaccus Ouyang & Li 1980	8	5	4	2						*	
Chordasporites impensus Ouyang & Li 1980		3								*	
C. orientalis Ouyang & Li 1980		4	3							*	
C. singulichorda Klaus 1960	4	5	2	1				*		–	
Colpectopollis pseudostriatus (Kopytova) Qu & Wang 1986		9	4	4						*	
C. scitulus (Qu & Pu) Qu & Wang 1986		6	2							*	
Enzonalasporites tenuis Leschik 1955	4	2					*			–	
E. vigens Leschik 1955	5		1				*			–	
Lueckisporites triassicus Clarke 1965	7	8			*					–	
Minutosaccus parcus Qu & Wang 1986	4	6	2							*	
Parcisporites rarus Ouyang & Li 1980	5	5	3	1						*	
P. solutus Leschik 1955	4	3					*			–	
Pinuspollenites normalis Qu & Wang 1986	7	4	3	2						*	
Platysaccus undulatus Ouyang & Li 1980		5	2	1						*	
Podocarpidites queenslandi (deJersey) Qu 1980		7								–	*

Table 1. (*Cont.*)

Spores and pollen	Regions				GB	DE	CH	AT	RO	CN	AU
	References				[1]	[2]	[3]	[4]	[5]	[6]	[7]
	Count of specimens in reservoirs										
	O	T	J	K	T_3	T	T_3	T_3	T	T	T
P. radialis (Leschik) Qu 1984	5	3					*			–	
Taeniaesporites divisus Qu 1982		5								*	
T. kraeuseli Leschik 1955	5	7					*			–	
T. rhaeticus Schulz 1967	4	4	3			*				–	
Total	217	312	99	42							

Abbreviations: O – Ordovician; T – Triassic; T_3 – Upper Triassic; J – Jurassic; K – Cretaceous; GB – Great Britain; DE – Germany, CH – Switzerland; AT – Austria; RO – Romania; CN – China; AU – Australia.
‘*’ indicates the original stratigraphic horizon of a taxon that was first described in this locality; ‘–’ indicates other stratigraphic ranges of this taxon that were subsequently described (but not the first record).
References: [1] Clarke, 1965; Batten & Coppelhus, 1996; [2] Schulz, 1967; Schulz, 1964; Mädler, 1964; [3] Leschik, 1955; [4] Klaus, 1960; [5] Venkatachala, Beju & Kar, 1968; [6] Yang *et al.* 1986; Qu, 1982; Ouyang & Li, 1980; Liu, 2003; [7] De Jersey, 1962; Balme, 1963; Playford, 1965.

Table 2. Jurassic spores and pollen in crude oils from reservoirs of different ages in the Tarim Basin and their distribution in the Jurassic strata of Eurasia, North America, Australia and New Zealand

Spores and pollen	Regions						GB	SE	RU	CN	CA	AU	NZ
	References						[1]	[2]	[3]	[4]	[5]	[6]	[7]
	Count of specimens in reservoirs												
	O	T	J	K	E	N	J_{1-2}	J_{1-2}	J	J	J	J	J
Spores													
Apiculatisporis ovalis (Nilsson) Norris 1967						11		*		–	–		
A. variabilis Pocock 1970		3	3		2	5				–	*		
Asseretospora amplectiformis Qu et Wang 1990		7	4						*	–		–	
A. anagrammensis Liu 2000		5	3						*	–		–	
A. scanicus Huang 1993		5	3	2				*		–		–	
Cibotiumspora paradoxa (Mal.) Chang 1965	4	5	7	4	3	8			*	–			
Concavisporites toralis (Leschik) Nilsson 1958		4	2					*		–			
Cyathidites australis Couper 1953	4	6	5	2	2	9	–			–			*
C. minor Couper 1953	8	9	7	5	7	24	–			–	–		*
Deltoidospora gradata (Mal.) Pocock 1970	3		6	3	3	8			*	–	–		
D. lineata (Bolch.) Pocock 1970						5			*	–	–		
D. perpusilla (Bolch.) Pocock 1970	5	4	7	3	2	14			*	–	–		
Dictyophyllidites harrisii Couper 1958	7	5	6	4	5	21	*			–	–		
Gleicheniidites conflexus (Chln.) Xu & Zhang 1980		6	4	3	2	4	*			–			
G. nilssonii Pocock 1970		5	3							–	*		
G. rousei Pocock 1970		4	3	3	1	17				–	*		
Granulatisporites jurassicus Pocock 1970		2	5	2	3	4				–	*		
G. minor de Jersey 1959		3	4	3	2	4				–		*	
Klukisporites variegatus Couper 1958						7	*			–			
Leptolepidites major Couper 1958						4	*			–			
L. verrucatus Couper 1953						4				–			*
Lycopodiumsporites paniculatoides Tralau 1968		5	2			3		*		–			
L. subrotundus (Kara-Murza) Pocock 1970		6	3			4			*	–	–		
Marattisporites scabratus Couper 1958	7		5		1		*			–			
Murospora jurassica Pocock 1970						5				–	*		
M. minor Pocock 1970						7				–	*		
Osmundacidites wellmanii Couper 1953	8	8	14	6	4	19	–		–	–			*
Todisporites major Couper 1958						7	*			–			
Undulatisporites concavus Kedves 1971 #1						7			–	–			
U. pflugii Pocock 1970	5	6	4	3						–	*		
Pollen													
Alisporites lowoodensis de Jersey 1963						4				–		*	
Bennettiteaepollenites lucifer (Thierg.) Potonie 1958 #2	2	5	5	3		7				–	–		
Callialasporites dampieri (Balme) Dev 1961			2							–		*	
C. minus (Tralau) Guy 1971		2	3					*		–			

Table 2. (*Cont.*)

	Regions						GB	SE	RU	CN	CA	AU	NZ
	References						[1]	[2]	[3]	[4]	[5]	[6]	[7]
	Count of specimens in reservoirs												
Spores and pollen	O	T	J	K	E	N	J_{1-2}	J_{1-2}	J	J	J	J	J
Cedripites minor Pocock 1970	5	4	7	3	2	9				–	*		
Cerebropollenites carlylensis Pocock 1970						4				–	*		
Chasmatosporites elegans Nilsson 1958						8		*		–			
C. major Nisson 1958						7		*		–			
C. minor Nilsson 1958						9		*		–			
Cycadopites minimus (Cookson) Pocock 1970 #[3]			7	8	4	14			–	–	–		
C. nitidus (Balme) Pocock 1970	9	8	14	5	4	17				–	–	*	
C. subgranulosus (Couper) Clarke 1965	7	3	9	3		16	*			–			
C. typicus (Mal.) Pocock 1970	4		8	4	5	12			*	–	–		
Paleoconiferus asaccatus Bolchovitina 1956						6			*	–	–		
Parvisaccites enigmatus Couper 1958			4	1		7	*			–			
Piceites expositus Bolchovitina 1956	2	4	5	2	3	6			*	–			
P. pseudorotundiformis (Mal.) Pocock 1970		5	3	2		4			*	–	–		
Pityosporites parvisaccatus de Jersey 1959		4	2							–		*	
Platysaccus lopsinensis (Mal.) Pocock 1970						7			*	–	–		
Podocarpidites florinii Pocock 1970						5				–	*		
P. langii Pocock 1970						5				–	*		
P. multicinus (Bolch.) Pocock 1970	3	2	3	2	1	7			*	–	–		
P. rousei Pocock 1970			4			4				–	*		
P. unicus (Bolch.) Pocock 1970	2		3		1	5			*	–	–		
P. wapellensis Pocock 1970						4				–	*		
Protopicea exilioides (Bolch.) Pocock 1970						4			*	–	–		
Protopinus scanicus Nilsson 1958						5		*		–			
Quadraeculina limbata Maljavkina 1949			3	1	2	5			*	–			
Vitreisporites itunensis Pocock 1970						3				–	*		
V. jansonii Pocock 1970						5				–	*		
V. jurassicus Pocock 1970						7				–	*		
V. shouldicei Pocock 1970						4				–	*		
Total	85	135	182	77	59	401							

Abbreviations: O – Ordovician; T – Triassic; J_{1-2} – Lower and Middle Jurassic; J – Jurassic; K – Cretaceous; E – Eocene; N – Neogene; GB – Great Britain; SE – Sweden; RU – Russia; CN – China; CA – Canada; AU – Australia; NZ – New Zealand.
References: [1] Couper, 1958; [2] Nilsson 1958; Tralau, 1968; [3] Maljavkina, 1949; Bolchovitina, 1956; [4] Sun,1989; Huang, 1995; Liu, 1982, 2003; Jiang & Wang, 2002; [5] Pocock, 1970; [6] Balme, 1963; De Jersey, 1959, 1963; [7] Couper, 1953.
'$*$' indicates the original stratigraphic horizon of a taxon that was first described in this locality; '–' indicates other stratigraphic ranges of this taxon that were subsequently described (but not the first record).
#[1] Hungary (Potonié, 1958); #[2]Germany (Potonié, 1958); #[3]Madagascar (Cookson, 1947).

from the three-part assemblage. The remainders of the assemblage are indicative for source and carrier beds. Generally, the oldest miospores in the assemblage indicate the source rocks, those of intermediate age indicate the carrier beds, and the youngest indicate the reservoir rocks (e.g. Jiang, 1988, 1990, 1991). Sometimes the three parts of the assemblage are coeval, indicating that the source rocks, carrier beds and reservoir rocks belong to the same formation (Jiang, 1988). Although the geological circumstances are often complicated, petroleum source rocks can be distinguished from non-source rocks by correlation of the palynological assemblages in crude oils and their supposed source rocks.

Triassic miospores in crude oils from the North Tarim Uplift are common in the Triassic deposit of the Tarim Basin. Twenty-one species of spores and pollen found in oils are also identified in the dark grey and black mudstone of the Lower Triassic Ehuobulake Formation; 37 miospore species identified in petroleum samples are found in the Middle Triassic Karamay Formation, and 44 species in petroleum samples are found in the dark grey and black mudstone of the Upper Triassic Huangshanjie and Taliqike formations (Table 4).

Jurassic miospores in crude oils from the North Tarim Uplift, the Kuqa Depression and the Southwest Tarim Depression are also common representatives in the Lower Jurassic and Middle Jurassic deposits of the basin. Forty-five species extracted from oils are also found in the dark grey and black mudstone of the Lower Jurassic Ahe and Yangxia formations, the Middle Jurassic Kezilenuer and Qiakemake formations in the North Tarim Uplift and the Kuqa Depression; 60 species found in oils are recorded in the dark grey and black mudstone of the Lower Jurassic Shalitashi and Kangsu formations, as well as the Middle Jurassic Yangye and Taerga formations in the Southwest Tarim Depression (Table 5).

The miospore assemblages identified in the crude oils are similar to those from the rocks of the Triassic and Jurassic successions. This indicates that

Table 3. Fungi, algae and acritarchs in crude oils of the Tarim Basin

Fungi, algae and acritarchs	North Tarim Yakela Oilfield	Southwest Tarim Kekeya Oilfield	Southwest Tarim Maigaiti Oilfield
Fungi			
Multicellaesporites ovatus Sheffy & Dilcher 1971		+	
M. pachydermus Ke & Shi 1978		+	
M. margaritus Ke & Shi 1978			+
Glomus sp.			+
Algae			
Pyrrhophyta			
Conicoidium cf. *granorugosum* Jiabo 1978	+		
C. sp.	+		
Dinogymnium granulatum Jiabo 1978		+	
Prominangularia cf. *dongyingensis* Jiabo 1978		+	
Rhombodella cf. *baculata* Jiabo 1978		+	
R. cf. *variabilis* Jiabo 1978		+	
R. sp.		+	
Tenua cf. *bellula* Jiabo 1978	++	+	
T. sp.	++		
Chlorophyta			
Campenia cf. *circellata* Jiabo 1978	++		+
Hungarodiscus cf. *punctatus* Jiabo 1978	++		
H. sp.	++		
Acritarchs			
Dictyotidium cf. *asperatum* Jiabo 1978	++		
D. sp.	++		
Granodiscus cf. *granulatus* Mädler 1963			+
Granoreticella sp.	++		
Heliospermopsis sp.	+		
Porusphaera sp.	++		+
Tectocorpidium cf. *rimosum* Jiabo 1978	+		
Verrucosphaera cf. *verrucosa* Jiabo 1978	+		
Acritarcha indet. Type 1	+		
Acritarcha indet. Type 2	+		
Acritarcha indet. Type 3	+		

See Figure 1 for locations. + rare, ++ common.

the palynomorphs in the crude oils were derived from Triassic and Jurassic plants, were deposited and released from these formations during primary migration, and migrated into different reservoirs during secondary migration. The correlation results between oils and rocks with palynomorphs suggest that the Triassic and Lower to Middle Jurassic deposits are important contributors to the petroleum source in the Tarim Basin (Fig. 2).

The colour of the Triassic and Jurassic miospores is dark orange to brown, both in the petroleum and in the rocks. The thermal alteration index (TAI) based on colour of spore/pollen ranges between 2.8 and 3.4. This thermal maturity belongs to the mature main phase of liquid petroleum generation (Traverse, 1988), and consequently the Triassic and Jurassic petroleum source rocks of the Tarim Basin belong to the mature source rock type. These results are supported by the evidence from organic geochemical analyses made on crude oils and their putative source rocks in the Tarim Basin. Based on the bulk geochemical analyses and correlation between crude oils and their supposed source rock extracts, it was concluded that Mesozoic strata, particularly Lower and Middle Jurassic strata deposits, comprise a potentially significant non-marine petroleum source sequence. T_{max} value of 429 °C to 449 °C and vitrinite reflectance (R_o) values of 0.47 % to 0.67 % indicate that these rocks are at or just below the threshold of oil generation, and samples collected within depocentre sections average higher R_o values ($R_o = 0.75$ % for one Middle Jurassic rock sample) (Graham *et al.* 1990; Hendrix *et al.* 1995). Analyses of coals and organic-rich shales show a dominance of terrestrial, higher plant components. Visual kerogen analysis indicates that vitrinite, inertinite and exinite are the dominant minerals, and elemental analysis characterizes most kerogen as type III (Hendrix *et al.* 1995). Pyrolysis–gas chromatography results show the prominence of alkene/alkane doublets, and suggest that the Jurassic strata are capable of liquid hydrocarbon generation. Biomarker correlations show that three-quarters of the petroleum samples are consistent with derivation from the Jurassic strata. The high Pr/Ph ratios for most extracts and oil samples (generally > 2.5) are consistent with a higher plant-dominated non-marine environment.

6. Environment of petroleum source rocks

Additional data have been accumulated for improving our understanding of the potential botanical relationships of major dispersed miospore taxa, based upon *in situ* spores of the Mesozoic plants as well as their extant relatives. The closest relatives to the miospores identified in this study include a broad range of plants (Table 6). The extant relatives to most

Table 4. Distribution of important Triassic miospore taxa in crude oils of the Triassic strata in the Tarim Basin

Spores and pollen	Ehuobulake Fm. (T_1)	Karamay Fm. (T_2)	Huangshanjie Fm. (T_3^1)	Taliqike Fm. (T_3^2)
Spores				
Apiculatisporis globosus (Leschik) Playford & Dettmann 1965		+	++	++
A. parvispinosus (Leschik) Qu 1980		++	++	++
A. spiniger (Leschik) Qu 1980	+	++	++	++
Aratrisporites coryliseminis Klaus 1960		+	++	++
A. fischeri (Klaus) Playford & Dettman 1965		+	++	+
A. granulatus (Klaus) Playford & Dettman 1965	+	++	++	++
A. paenulatus Playford & Dettmann 1965		+	++	+
A. parvispinosus Leschik 1955			+	++
A. paraspinosus Klaus 1960			+	++
A. scabratus Klaus 1960	+	++	++	++
A. strigosus Playford 1965		++	++	++
A. tenuispinosus Playford 1965		+	+	++
Asseretospora gyrata (Playf. & Dettm.) Schuurman 1977			++	++
Calamospora nathorstii (Halle) Klaus 1960	+	++	++	++
C. tener (Leschik) Mädler 1964			++	++
Camarozonosporites rudis (Leschik) Klaus 1960			+	++
Conbaculatisporites mesozoicus Klaus 1960		+	++	++
Limatulasporites dalongkouensis Qu & Wang 1986	++			
L. parvus Qu & Wang 1986	++	+		
Lophotriletes corrugatus Ouyang & Li 1980	++			
Lundbladispora nejburgii Schulz 1964	+	++		
L. playfordi Balme 1963	++			
L. plicata Bai 1983	+	++		
L. subornata Ouyang & Li 1980	++			
Lycopodiacidites kuepperi Klaus 1960			++	++
L. rhaeticus Schulz 1967			++	++
Multinodisporites junctus Ouyang & Li 1980	++	+		
Osmundacidites alpinus Klaus 1960			++	++
Punctatisporites ambiguus Leschik 1955			++	+
P. microtumulosus Playford & Dettmann 1965		+		++
P. triassicus Schulz 1964	+	++	+	+
Retusotriletes arcticus Qu & Wang 1986	++	+		
R. mesozoicus Klaus 1960		+	++	++
Tigrisporites halleinis Klaus 1960		+	++	+
Verrucosisporites contactus Clarke 1965		+	++	++
V. remyanus Mädler 1964		+	+	++
Zebrasporites kahleri Klaus 1960			+	++
Pollen				
Alisporites aequalis Mädler 1964			++	++
A. australis de Jersey 1962		++	++	++
A. fusiformis Ouyang & Li 1980	++			
A. parvus de Jersey 1962		++	++	++
Cedripites parvisaccus Ouyang & Li 1980	++	+		
Chordasporites impensus Ouyang & Li 1980	++			
C. orientalis Ouyang & Li 1980	++			
C. singulichorda Klaus 1960		+	++	+
Colpectopollis pseudostriatus (Kopytova) Qu & Wang 1986		++	++	++
C. scitulus (Qu & Pu) Qu & Wang 1986		++	++	++
Enzonalasporites tenuis Leschik 1955			++	++
E. vigens Leschik 1955			+	++
Lueckisporites triassicus Clarke 1965		+	++	++
Minutosaccus parcus Qu & Wang 1986		++	+	+
Parcisporites rarus Ouyang & Li 1980	++	+		
P. solutus Leschik 1955			+	++
Pinuspollenites normalis Qu & Wang 1986		++	++	+
Platysaccus undulatus Ouyang & Li 1980	++			
Podocarpidites queenslandi (deJersey) Qu 1980		++	++	++
P. radialis (Leschik) Qu 1984		+	++	+
Taeniaesporites divisus Qu 1982	++	+		
T. kraeuseli Leschik 1955		+	+	++
T. rhaeticus Schulz 1967			++	++

+ rare, ++ common.
Abbreviations: Fm – Formation; T_1 – Lower Triassic; T_2 – Middle Triassic; T_3^1 – lower Upper Triassic; T_3^2 – middle Upper Triassic
For references to authors of taxon, see Tables 1 and 2 and reference list.

Table 5. Distribution of important Jurassic miospore taxa in crude oils of the Jurassic strata in the Tarim Basin

	North Tarim				Southwest Tarim			
Spores and pollen	Ahe Fm. ($J_1{}^1$)	Yangxia Fm. ($J_1{}^2$)	Kezilenuer Fm. ($J_2{}^1$)	Qiakemake Fm. ($J_2{}^2$)	Shalitashi Fm. ($J_1{}^1$)	Kangsu Fm. ($J_1{}^2$)	Yangye Fm. ($J_2{}^1$)	Taerga Fm. ($J_2{}^2$)
Spores								
Apiculatisporis ovalis (Nilsson) Norris 1967							++	++
A. variabilis Pocock 1970			++				++	+
Cibotiumspora paradoxa (Mal.) Chang 1965	+	++	++	+	+	++	++	++
Concavisporites toralis (Leschik) Nilsson 1958		++	++			+	+	
Cyathidites australis Couper 1953	+	++	++	++	+	++	++	++
C. minor Couper 1953	++	+++	+++	+++	++	+++	+++	+++
Deltoidospora gradata (Mal.) Pocock 1970			+	+		+	++	++
D. lineata (Bolch.) Pocock 1970							++	+
D. perpusilla (Bolch.) Pocock 1970	+		++	++		+	++	++
Dictyophyllidites harrisii Couper 1958	+	++	++	++		+++	+++	++
Duplexisporites amplectiformis (Kara-Murza) Playford & Dettmann 1965		++	++	+				
D. anagrammensis (Kara-Murza) Playford & Dettmann 1965			++	+			+	
D. scanicus (Nilsson) Playford & Dettmann 1965			++	+				
Gleicheniidites conflexus (Chln.) Xu & Zhang 1980			++	++			++	++
G. nilssonii Pocock 1970			++	++			+	
G. rousei Pocock 1970			++				++	+
Granulatisporites jurassicus Pocock 1970		++	++	++		++	++	++
G. minor de Jersey 1959	+	++			+	++		
Klukisporites variegatus Couper 1958		+	++	+		+	++	+
Leptolepidites major Couper 1958							++	++
L. verrucatus Couper 1953						+	++	+
Lycopodiumsporites paniculatoides Tralau 1968			++	++			+	+
L. subrotundus (Kara-Murza) Pocock 1970		++	++	+		+	+	+
Marattisporites scabratus Couper 1958			++	++			++	++
Murospora jurassica Pocock 1970							++	+
M. minor 1970							++	+
Osmundacidites wellmanii Couper 1953	+	++	++	++	+	++	++	++
Todisporites major Couper 1958							++	+
Undulatisporites concavus Kedves 1971							++	+
U. pflugii Pocock 1970			++				+	
Pollen								
Alisporites lowoodensis de Jersey 1963		++				+	+	
Bennettiteaepollenites lucifer (Thierg.) Potonie 1958			++	++			++	++
Callialasporites dampieri (Balme) Dev 1961			+	+			++	+
C. minus (Tralau) Guy 1971			++	++			++	+
Cedripites minor Pocock 1970		++	++	++		++	++	++
Cerebropollenites carlylensis Pocock 1970			+	+			++	++
Chasmatosporites elegans Nilsson 1958		+				++	+	
C. major Nisson 1958		+				++		
C. minor Nilsson 1958						++	+	
Cycadopites minimus (Cookson) Pocock 1970			+	+			++	++
C. nitidus (Balme) Pocock 1970	+	++	++	++	+	++	++	++
C. subgranulosus (Couper) Clarke 1965		++	++			++	++	+

Table 5. (*Cont.*)

Spores and pollen	North Tarim				Southwest Tarim			
	Ahe Fm. (J_1^1)	Yangxia Fm. (J_1^2)	Kezilenuer Fm. (J_2^1)	Qiakemake Fm. (J_2^2)	Shalitashi Fm. (J_1^1)	Kangsu Fm. (J_1^2)	Yangye Fm. (J_2^1)	Taerga Fm. (J_2^2)
C. typicus (Mal.) Pocock 1970	+	++	++	++		++	++	++
Paleoconiferus asaccatus Bolchovitina 1956		+	+	+		+	++	+
Parvisaccites enigmatus Couper 1958			+	+			++	+
Piceites expositus Bolchovitina 1956			++	++			++	++
P. pseudorotundiformis (Mal.) Pocock 1970	+	++	++	++		+	+	+
Pityosporites parvisaccatus de Jersey 1959	+	++				+		
Platysaccus lopsinensis (Mal.) Pocock 1970							++	+
Podocarpidites florinii Pocock 1970							++	+
P. langii Pocock 1970							+	++
P. multicinus (Bolch.) Pocock 1970	+	++	++			++	++	
P. rousei Pocock 1970				+			++	++
P. unicus (Bolch.) Pocock 1970			+	+			++	+
P. wapellensis Pocock 1970							+	++
Protopinus scanicus Nilsson 1958		++	+			++	++	
Protopicea exilioides (Bolch.) Pocock 1970			+	+			++	++
Quadraeculina limbata Maljavkina 1949		++	++	+		+	++	++
Vitreisporites itunensis Pocock 1970			++	++			++	+
V. jansonii Pocock 1970							++	
V. jurassicus Pocock 1970							++	+
V. shouldicei Pocock 1970							++	

\+ rare, ++ common, +++ abundant.
Abbreviations: Fm. – Formation; $J_1{}^1$ – lower Lower Jurassic; $J_1{}^2$ – middle Lower Jurassic; $J_2{}^1$ – lower Middle Jurassic; $J_2{}^2$ – middle Middle Jurassic.

Table 6. Botanical relationships of major dispersed spore/pollen genera identified in crude oils of the Tarim Basin

Pteridophyta	Gymnospermae
Lycopsida	**Pteridospermopsida**
Pleuromeiaceae	Caytoniales
Aratrisporites (Leschik) Klaus	*Vitreisporites* (Leschik) Jansonius
Lycopodiaceae	Incertae sedis
Camarozonosporites (Potonié) Klaus	*Alisporites* Daugherty
Lycopodiumsporites Thiergart	**Cycadopsida**
Selaginellaceae	Cycadales or Ginkgoales
Lundbladispora Balme	*Cycadopites* (Wodehouse) Wilson & Webster
Filicopsida	Bennettiales (?)
Marattiaceae	*Bennettiteaepollenites* Thiergart
Marattisporites Couper	Incertae sedis
Osmundaceae	*Chasmatosporites* Nilsson
Osmundacidites Couper	**Coniferopsida**
Todisporites Couper	Podocarpaceae
Schizaeaceae	*Parvisaccites* Couper
Klukisporites Couper	*Platysaccus* (Naumova) Potoniè & Kremp
Gleicheniaceae	*Podocarpidites* (Cookson) Potonié
Gleicheniidites (Ross) Delcourt et Sprumont	Pinaceae
Cyatheaceae	*Cedripites* Wodehouse
Cyathidites Couper	*Piceaepollenites* Potonié
Deltoidospora (Miner) Potonié	*Piceites* Bolchovitina
Dicksoniaceae	*Pinuspollenites* Raatz
Cibotiumspora Chang	Araucariaceae
Cyathidites Couper	*Callialasporites* Dev
Dipteridaceae or Cheiropleuriaceae or Matoniaceae	
Concavisporites (Pflug) Delcout & Sprumont	
Dictyophyllidites Couper	
Granulatisporites (Ibrahim) Potonié & Kremp	

This summary is based upon comprehensive results of the *in situ* spore studies of the Mesozoic plants and their living relatives based on major references: e.g. Couper, 1958; Nilsson, 1958; Potonié, 1962; Townrow, 1962; Chang, 1965; Helby & Martin, 1965; Grauvogel-Stamm, 1978; Van Konijnenburg-Van Cittert, 1971, 1975, 1978, 1981, 1989, 1993; Litwin, 1985; Traverse, 1988; Balme, 1995; Wang, 1999, 2002; Wang & Mei, 1999; Wang *et al.* 2001; Abbink, 1998 and the studies on extant spores and pollen from living plants: e.g. Zhang *et al.* 1976; Wang *et al.* 1995.

of these plants are humidogene thermophytes. For instance, lycophytes grow on acidic soils in humid climates; the marattialean ferns are large and tall plants, presently growing in the tropical or subtropical forests; the tree ferns (represented by *Cyathidites*, for example, in the spore record) are growing in temperate–tropical humid areas; and several ground fern taxa (Table 6) are distributed in the tropical and subtropical swamp/marsh lands as understory vegetation. The cycads are typical thermophytes, and so are several of the conifer taxa identified in the miospore assemblages. A case analysis on the Jurassic rock palynomorphs, their affinities, vegetation reconstruction and climatic implications was carried out in the Qaidam Basin, a giant petroliferous Mesozoic basin near the Tarim Basin, northwest China (Wang, Mosbrugger & Zhang, 2005). In summary, the ecological characteristics of the parent plants to which the spores and pollen in this study belong suggest that they grow in warm and humid climate conditions.

The algae in crude oils of the Tarim Basin (Table 3) are informative for interpreting the depositional environments of petroleum source rocks. Pyrrhophyta algae are related to the marine environment, and dinoflagellates usually indicate marine conditions. Chlorophyte algae are mostly produced in freshwater bodies, and *Pediastrum* indicates typical freshwater conditions. Neither dinoflagellates nor *Pediastrum* are found in the petroleum or source rocks of the basin, therefore the depositional environments of the petroleum source rocks are supposed to be neither brines of the marine environment nor typical freshwater. The ecological conditions reflected by the palynology show that the source rocks were probably formed in swamps in brackish to lacustrine environments during warm and humid climatic conditions.

The odd-carbon-chain n-paraffin and olefins are synthesized by marine plants primarily in the C_{15} to C_{21} range and by land plants primarily in the C_{27} to C_{35} range. Brackish-water plants synthesize in the intermediate range C_{19} to C_{27} (Hunt, 1979). Hendrix *et al.* (1995) reported that the dominant n-alkane is either n-C_{21}, n-C_{23}, or n-C_{25}, and a slight to pronounced odd-over-even preference (OEP) is present in the Jurassic rock sample from the Tarim Basin. The dominance of n-alkane (n-C_{21} to n-C_{25}) suggests that the source rocks were deposited in a brackish-water sedimentary environment.

7. Mechanisms of petroleum migration as shown by palynomorphs

Spore/pollen grains which were originally buried in the sediments have contributed their waxy, fatty and oily secretions to the formation of petroleum, leaving only their decay-resistant remains. These fossil spores and pollen could migrate along with liquid and gaseous hydrocarbons; some of them enter petroleum accumulations, and provide information about passage, direction and route of petroleum migration (Jiang, 1991; Jiang & Yang, 1994, 1999).

The primary migration means the migration of original petroleum from the petroleum source bed. Original petroleum could likely not exit through source rock pore networks, because the pore diameters of petroleum source rocks are generally less than 0.01 μm, and the oil droplet diameters are usually bigger than 1 μm (Tissot & Welte, 1978; Li, 2004). Palynomorphs in petroleum are generally larger than 15 μm in diameter and the pores of source rocks are too small for their passage. Therefore, the presence of miospores derived from petroleum source rocks in crude oils suggests that the possible pathways of petroleum primary migration could be via microfissures in the source rocks, not via pore space. Microfissures formed by abnormal high pressure during the process of diagenesis are common, and such microfissures are presumably available for initial migration and expulsion of petroleum (Tissot & Welte, 1978; Roehl, 1981; Hua & Lin, 1989; Li, 2004). The width of the microfissures is generally less than 100 μm (Li, 2004). Hua & Lin (1989) reported that microfissures fields with bitumen can be observed under microscope in the Upper Jurassic to Lower Cretaceous mudstone from the Jiuxi Basin, China. This is evidence for microfissures serving as pathways of petroleum primary migration. Fossil miospores have the ability to pass through various migration pathways, as they are very thin and flexible. When the hydrocarbon fluid power is strong, the fossil spores and pollen can be pressed into wrinkles and pass through narrow pathways, and subsequently recover their original state when the space around them increases; this flexibility can be observed under the microscope (Jiang & Yang, 1992).

Pore networks associated with secondary migration, such as connected porous openings, interstratified openings, joint fissures, fault fissures and unconformity surfaces, all provide an avenue for migration of expelled spores and pollen away from the source rock. Larger structures (such as faults and unconformities) are also well developed in the Tarim Basin and as previously outlined, and crude oil samples collected from the wells near faults or unconformity surfaces contain numerous spores and pollen.

The phase state of petroleum migration depends in essence on the passages of petroleum migration. Because microfissures are wide enough for the passage of miospores, the passageways must be unblocked for the passage of oil droplets. It follows that the migration of petroleum in the liquid phase is fully possible in the course of primary migration. Liquid phase migration is also common in the course of secondary migration, because the passageways generally are much wider than microfissures.

The palynological results indicate that the routes of petroleum migration in the Tarim Basin mainly are from the Triassic or Jurassic petroleum source rocks to the different petroleum reservoirs, such as the Ordovician, Triassic, Jurassic, Cretaceous and Tertiary

Table 7. Directions and routes of petroleum migration in the Tarim Basin

Oil fields/ Reservoirs	Source beds	Reservoir beds	Migration directions	Migration routes
Kelatu	J	N	Vertical	J→N
Kekeya	J	N	Vertical	J→N
Yiqikelike K	J	K	Vertical	J→K
Yiqikelike J	J	J	Lateral	J→J
Yingmaili	J	E	Vertical	J→E
Yakela K	J	K	Vertical	J→K
	T		Vertical	T→K
Yakela J	J	J	Lateral	J→J
(Lunnan J)	T		Vertical	T→J
Yakela T	J	T	Vertical	J→T
(Lunnan T)	T		Lateral	T→T
Yakela O	J	O	Vertical /Lateral	J→O
(Lunnan O)	T		Vertical /Lateral	T→O

Abbreviations: O – Ordovician; T – Triassic; J – Jurassic; K – Cretaceous; E – Eocene; N – Neogene.

reservoirs. Both vertical and lateral migrations are important in the course of petroleum migration in the Tarim Basin. Importantly, structural deformation could complicate the theory that the occurrence of older palynomorphs in younger reservoir strata requires vertical secondary migration. If structural deformation juxtaposes source rocks and reservoir rocks laterally, lateral migration may be more important. The later juxtaposition of source rocks and reservoir rocks as a consequence of structural deformation, such as Triassic or Jurassic source rocks and Ordovician reservoir rocks, is a possible scenario in the Tarim Basin. Based on the study of palynomorphs in petroleum, the directions and routes of petroleum migration are summarized in Table 7. The petroleum migration routes were complicated in the northern Tarim Basin and relatively simple in the southwestern Tarim Basin.

8. Conclusions

The following conclusions may be drawn from the present study:

(1) The palynomorphs identified from crude oils and rocks in the Triassic and Jurassic of the Tarim Basin provide informative evidence for determining the potential petroleum source rocks. The results of this investigation indicate that dark-coloured argillaceous rocks of the Lower Triassic Ehuobulake Formation, the Middle Triassic Karamay Formation, the Upper Triassic Huangshanjie and Taliqike formations, the Lower Jurassic Yangxia Formation, and the Middle Jurassic Kezilenuer and Qiakemake formations are the probable petroleum source rocks in the northern Tarim Basin. The dark-coloured argillaceous rocks of the Lower Jurassic Kangsu Formation and the Middle Jurassic Yangye and Taerga formations are the probable petroleum source rocks in the southwestern Tarim Basin.

(2) The thermal alteration index (TAI) based on colour of spore/pollen indicates that the Triassic and Jurassic dark-coloured argillaceous rocks in the Tarim Basin are mature petroleum source rocks. This conclusion is supported by the results of organic geochemical analyses. The vitrinite reflectance (R_o) of the Jurassic rocks from the northern Tarim depocentre reaches 0.75 %, within the oil window.

(3) The botanical affinities of the spores and pollen identified in crude oils of the Tarim Basin include mosses, ferns, cycads and conifers, and most of these plants prefer warm and humid climates. The ecological characteristics of the palaeoflora indicate that the Triassic and Jurassic petroleum source rocks were formed in brackish to lacustrine swamps during warm and humid climate conditions.

(4) Judging from the palynomorphs, it may be concluded that microfissures formed by abnormal high pressure during the diagenesis and catagenesis of petroleum source rocks could provide pathways for the primary migration of petroleum. Faults, unconformity surfaces, joints and other fissures could provide passages for the secondary migration of petroleum. The main direction of petroleum migration could be represented by either vertical migration or lateral migration for different reservoir types, and the routes of petroleum migration would be determined by different source beds and different reservoir beds.

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