

Cretaceous source rocks and associated oil and gas resources in the world and China: A review

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Abstract: The Cretaceous is one of the most important stratigraphic intervals for hydrocarbon source rocks. This article summarizes the distribution, formation, and development characteristics of Cretaceous source rocks and associated oil and gas resources in the world and China, aiming at improving the understanding of this hydrocarbon enrichment and at broadening domestic exploration. Outside China, these rocks are generally formed in marine or transgressive environments during both the Upper and Lower Cretaceous. The majority of Cretaceous source rocks are located in the Persian Gulf, Mediterranean, and Gulf Coast of the USA. Kerogen types within these source rocks have distinct spatial distribution characteristics, with high-latitude Boreal Realm, Tethyan Realm and South Gondwana Realm source rocks containing type III, II, II-III kerogens, respectively. Cretaceous source rocks in China can be mainly divided into four zones: Eastern, Central, Northwest, and Qinghai–Tibet Plateau zones. The majority of Chinese source rocks formed in the Early Cretaceous, whereas the most productive source rocks are developed in the Upper Cretaceous, such as those within the Songliao Basin. Most of these basins are formed in lacustrine environments, although some may have been influenced by transgressive events. Cretaceous source rocks are formed in four distinctive ways: 1) during Oceanic Anoxic Events and associated global sea-level rises, 2) in Black Sea–type retention basins, 3) during transgression and 4) during periods of significant terrestrial input. Formation of these source rocks is controlled by four factors: paleoclimate, paleotopography, transgression, and Oceanic Anoxic Events. These four major controlling factors indicate that China’s hydrocarbon exploration within the Cretaceous should focus on two key areas with extremely low exploration levels, the Qinghai–Tibet Plateau and the southeastern coast of China.

Key words: Cretaceous, source rock, organic matter, Tethys, transgression

1 Introduction

Global oil and gas exploration has shown that the majority of the world’s hydrocarbon source rocks were formed during the Cretaceous, with approximately 60% of the world’s oil and gas fields being associated with source rocks of the Albian–Coniacian period (Irving et al, 1974). A significant number of petroliferous basins are linked with Cretaceous source rocks, including the well-known Persian Coast–Zagros Basin in the Middle East, the Maracaibo Basin in Venezuela, and the Songliao Basin in China. In addition, hydrocarbon resources in some basins are derived in part from Cretaceous source rocks, such as the Western Siberia Basin in Russia, the Gulf of Mexico Basin, foreland basins of the Rocky Mountains, and the North Slope Basin in North

America. The links between significant oil and gas resources and Cretaceous source rocks as described above mean that it is important to understand the processes involved in the development of Cretaceous source rocks. In addition, the Cretaceous is an important period in Earth’s evolution, and is associated with major geological events, including a number of Oceanic Anoxic Events (OAEs) and the development of Cretaceous Oceanic Red Beds (CORB) (Huang et al, 2008; Jenkyns, 2010; Wang et al, 2011). This implies that identifying the characteristics and processes involved in the formation of these Cretaceous source rocks has broad geological significance. However, previous works focused mostly on case studies, with relatively few comprehensive summaries and analyses. Therefore, in this paper, we review Cretaceous source rocks and petroleum systems in China and other countries worldwide, summarize the distribution and characteristics of these rocks, the processes and controls involved in their formation, and provide suggestions for

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future exploration for Cretaceous oil and gas in China. This aims at improving the understanding of this hydrocarbon enrichment and to broaden domestic exploration.

2 Characteristics of global Cretaceous source rocks and associated oil and gas resources

According to Klemme and Ulmishek (1991), global oil and gas resources can be divided into four realms: Tethyan, Boreal, Pacific, and South Gondwana (Fig. 1). Cretaceous source rocks are developed in all of these four realms.

2.1 Tethyan Realm

The Tethyan Realm covers the middle- to low-latitude

areas of the world, from the Gulf of Mexico Coast and northern South America to the southeast of China and the South China Sea. This realm contains the world's two largest gas fields (i.e., the North Field in Qatar and the South Pars field in Iran), 9 out of 10 world's biggest oil fields (Bai, 2006; 2007). In general, it contains approximately 68% of Earth's hydrocarbon resources in only 17% of Earth's continental shelf and land mass, about 5 times of the resources in the Boreal Realm, 13 times those of the Pacific Realm, and 40 times those of the South Gondwana Realm. Thus, the Tethyan Realm is the most productive for oil and gas resources of the four realms (i.e., Tethyan, Boreal, Pacific, and South Gondwana; Fig. 1).

The main petroliferous basins within this realm related to

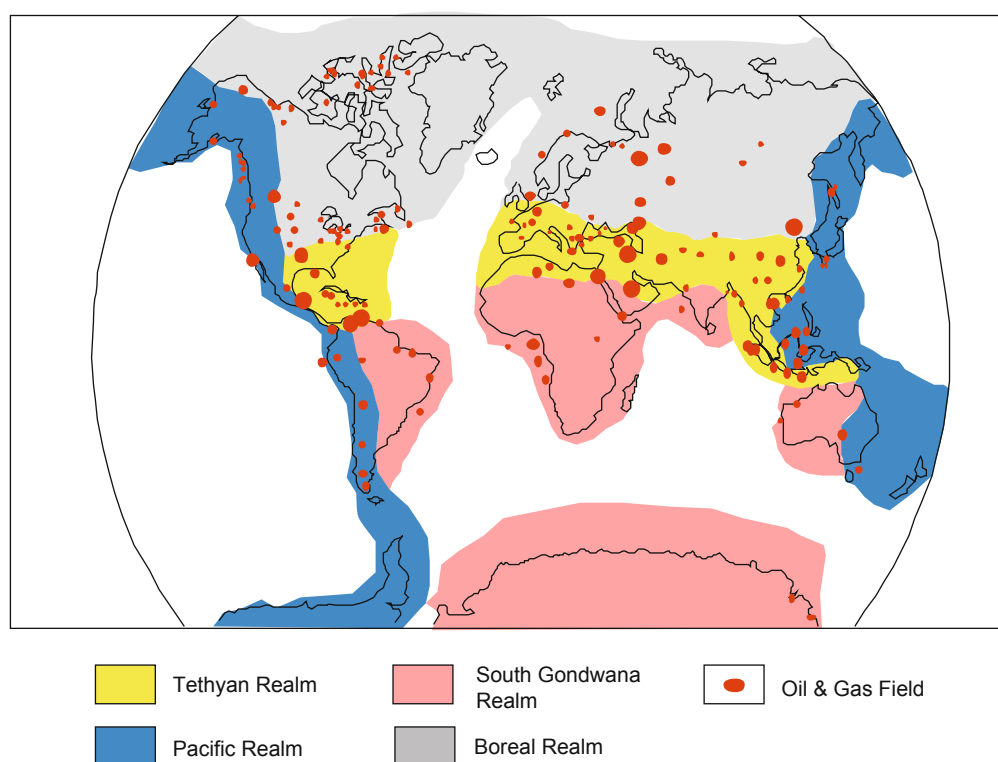


Fig. 1 The four global oil and gas realms (modified after Klemme and Ulmishek, 1991). Size of the red points indicates the scale and significance of the oil/gas field

Cretaceous source rocks include the Persian Coast–Zagros Basin in the Middle East, the Maracaibo Basin, the East Venezuela Basin, the Venezuelan Magdalena Basin, the North American Gulf Coast, and the Sirt Basin of north Africa. The majority of Cretaceous source rocks within this realm are marine carbonate rocks and shales that contain type II kerogen (Table 1). These Cretaceous source rocks, commonly together with carbonate reservoirs and gypsum or mudstone caprocks, form source–reservoir–cap rock combinations (Palacas et al, 1984; Tian et al, 2008; Xu et al, 2010; Jia et al, 2011; Zhao et al, 2011; Nabikhani et al, 2012; Qin et al, 2012; Quintero et al, 2012; Zhang et al, 2012).

2.2 Boreal Realm

The Boreal Realm lies to the north of the Tethyan Realm

and is outside of the Pacific Rim Arc basin system, covering the middle- to high-latitude areas of the world. This realm has the second highest proportion total hydrocarbon resources after the Tethyan Realm, containing approximately 23% of Earth's hydrocarbon resources in 28% of Earth's continental shelf and land mass. The main petroliferous basins within this realm related to Cretaceous source rocks include the Russian West Siberia Basin, the Alaskan North Slope Basin, the Alberta–Western Canada foreland basin, and the Scotia Basin of the North American passive continental margin. The West Siberia Basin contains the world's largest natural gas reserves (Schaefer et al, 1999; Bai, 2006), and the famous petroliferous Songliao Basin in China is also within this Boreal Realm. This realm contains both marine shale and lacustrine clastic source rocks that are dominated by type III kerogen, but with

Table 1 Cretaceous source rocks within Tethyan Realm basins (after Parsons et al, 1980; Palacas et al, 1984; El-Alami, 1996; Robison, 1997; Alberdi-Genolet and Tocco, 1999; Rangel et al, 2000; Rabbani and Kamali, 2005; Tian et al, 2008; Qin et al, 2012)

Basin	Gulf of Mexico Coast	Gulf of Mexico Coast	Magdalena	Maracaibo	Maracaibo	East Venezuela	Sirt	Persian Gulf-Zagros	Persian Gulf-Zagros	Persian Gulf-Zagros
Location	South Florida	Texas	Columbia	Venezuela	Venezuela	Venezuela	Libya	Middle East	Middle East	Middle East
Period	K ₁	K ₂	K ₂	K ₂	K ₁	K ₂	K ₂	K ₁	K ₁	K ₂
Formation	Sunniland	Eagle Ford	La Luna	La Luna	Machiques	Guayuta	Sirt	Kazhdumi	Gadvan	Gurpi
Lithology	Limestone, shale	Limestone, shale	Carbonate, shale	Carbonate, shale	Carbonate	Carbonate, shale	Shale	Bituminous limestone	Carbonate	Carbonate
Sedimentary facies	Marine	Marine	Marine	Marine	Marine	Marine	Transgressive	Marine	Marine	Marine
TOC, %	2.5	4	0.9-4.6	0.5-8.5	1-5.5	0.25-6.6	1.9	1.57	1.32	1.02
HI, mg/g TOC	608	300-400	14-523	10-460	10-300	/	300-600	208	255	475
Kerogen type	II	II	II	II	II	II, III	II	II	II	II
R _o , %	0.4-0.6	0.6	/	0.95-1.04	1-1.08	0.5-2.0	0.71-1.62	0.56-1.08	/	0.8

Note: “/” denotes no data available

some source rocks containing type I and II kerogens (Table 2). The majority of Cretaceous source rocks in this realm form source–reservoir–cap rock combinations within the same units

or with adjacent sandstone reservoir and shale cap-rock units (Gentzis et al, 2008; Aleksandrova et al, 2010; Creaney and Sullivan, 2011; Yao et al, 2011; Gao et al, 2011).

Table 2 Cretaceous source rocks within Boreal Realm basins (after Powell, 1982; Moshier and Waples, 1985; Anders and Magoon, 1986; Schaefer et al, 1999; Peters et al, 2006)

Basin	North Slope	North Slope	Alberta	Alberta	Scotia	West Siberia	Songliao	Songliao
Location	Alaska	Alaska	North America	North America	North America	Russia	China	China
Period	K ₁	K _{1,2}	K ₁	K ₂	K ₁	K _{1,2}	K ₂	K ₂
Formation	Pebble Shale Unit	Hue Shale	Mannville	Colorado	Verrill Canyon	Pokur	Qingshankou	Nenjiang
Lithology	Shale	Shale	Coal-bearing sequence, calcareous shale	Shale	Mudstone	Coal-bearing sequence	Mudstone	Mudstone
Sedimentary facies	Marine	Marine	Transgression	Marine	Lacustrine transgression	Lacustrine	Lacustrine transgression	Lacustrine transgression
TOC, %	1.47-4.41	1.57-5.53	2	1.5	1.5	5-62	1.57	2.02
HI, mg/g TOC	26-341	31-400	/	450	/	128-303	/	/
Kerogen type	III	II, III	III	II	III	III	I, II	I, II
R _o , %	0.5-1.8	0.5-1.8	1-2	0.9-1.2	1-1.5	0.4-0.6	0.5-0.8	0.5-0.8

Note: “/” denotes no data available

2.3 South Gondwana Realm

The South Gondwana Realm occurs south of the Tethyan Realm, extending from the central west of South America to eastern Australia. This realm covers 38% of global land and continental shelf areas, but only contains 4% of the world’s oil and gas reserves, indicating that this realm is relatively poorly petroliferous. The main Cretaceous source rocks in this realm are located in passive continental margin basins within the South Atlantic; these basins were formed during the breakup of Gondwana and post-Cretaceous expansion of the South Atlantic (He et al, 2011; Beglinger et al, 2012). The progression of this breakup caused the formation of three different types of source rocks: lacustrine deltaic clastic rocks during rifting, lagoon shales during transitional periods, and marine shales during drifting. These source rocks contain

both type II and III kerogens in general (Table 3).

2.4 Pacific Realm

The Pacific Realm includes arc basins of the Pacific Rim, the east coast of Australia, and the west coast of North and South America, and covers 17% of global land and continental shelf areas, but only 5% of the world’s oil and gas reserves. This indicates that, as was the case for the South Gondwana Realm, it is relatively poorly petroliferous. The majority of source rocks in this realm were formed during the Tertiary (Корчагин and Shi, 1996), although some Cretaceous source rocks are randomly present in the Neuquén Basin of Argentina and other small sedimentary basins; however, few basins hosting significant Cretaceous source rocks are known within this realm.

Table 3 Cretaceous source rocks within basins of the South Atlantic (after Guardado et al, 2000; Schoellkopf and Patterson, 2000; Harris et al, 2004; Balbinot and Kalkreuth, 2010; He et al, 2011; Qiu and Liu, 2012; Sachse et al, 2012)

Basin	Reconcavo	Santos	Santos	Campos	Potiguar	Tarfaya	Gabon	Gabon	Congo	Lower Congo	Lower Congo
Location	Eastern Brazil	Eastern Brazil	Eastern Brazil	Eastern Brazil	Eastern Brazil	Morocco	Gabon	Gabon	Congo	Congo, Angola	Congo, Angola
Period	K ₁	K ₁	K ₂	K ₁	K ₁	K ₂	K ₁	K ₂	K ₁	K ₁	K ₂
Formation	Candeias	Guaratiba	Itajai-Acu	Lagoa feia	Alagamar	Upper Cretaceous	Melania	Upper Cretaceous	Lower Cretaceous	Bucomazi	Labe
Lithology	Sandstone shale	Shale limestone	Shale	Mudstone	Shale, limestone	Shale	Shale underlying the salt	Shale overlying the salt	Shale	Calcareous mudstone	Shale
Sedimentary facies	Lacustrine brackish	Lagoon	Marine	Transitional	Transitional	Marine	Deep lacustrine	Deep marine	Lacustrine-delta	River-shallow lake	Marine
TOC, %	0.72-1.60	2-6	0.2-1.9	1-5	4-6	1-19	6.1	3-6	2.5	0.5-5	1-5
HI, mg/g TOC	44-350	/	200	250-750	500-700	750	400-900	>400	300	100-300	100-550
Kerogen type	II	I	II, III	I, II	I, II	I	I, II	II, III	II, III	III	II
R _o , %	0.46-0.86	Large variation	0.5-0.8	0.4-0.6	/	0.3-0.4	0.5-1	0.5-1	<0.55	/	/

Note: “/” denotes no data available

In summary, global basins outside China that host Cretaceous source rocks are generally located in coastal and continental shelf environments. These source rocks were deposited mostly within marine or transgressive environments, and few basins have source rocks that were not influenced by transgression. In terms of hydrocarbon prospects, there appears to be little obvious temporal difference between Upper and Lower Cretaceous source rocks, but it should be noted that the majority of Cretaceous source rocks are spatially located around the Persian Gulf, the Mediterranean, and the Gulf of Mexico Coast.

Kerogen types and source–reservoir–cap rock combinations are distributed like bands in these different realms. Middle- and high-latitude Boreal Realm source rocks are dominated by shales, mudstones and some coal-bearing sequences that mainly contain type III kerogen, although some rocks, such as those of the China’s Songliao Basin, may contain type I and II kerogens. Petroleum systems in this realm consist of sandstone reservoirs with mudstone or shale being cap rocks. In contrast, Cretaceous source rocks in the low-latitude Tethyan Realm are generally carbonates or shales that contain type II kerogen and form petroleum systems with carbonate reservoirs and gypsum or shale cap rocks. Cretaceous source rocks and petroleum systems in the South Gondwana Realm have characteristics indicative of a mix between the Tethyan and Boreal realms, reflecting differences of formation mechanisms of source rocks (see detailed discussion later).

3 Basic characteristics of Cretaceous source rocks and associated oil and gas resources in China

Petroliferous basins containing Cretaceous source rocks in China mainly include the Songliao Basin and its peripheral basins, the Hailar, Erlian, Jiaolai, Subei, western Taiwan, southwestern Taiwan, Lile, Yin’e, Gonghe, southern Junggar, Qiangtang, Cuoqin, Biru, and Bolin basins, the coast of

southeastern China, and basins of the Hexi Corridor. The majority of these Chinese Cretaceous petroliferous basins (except for Tibet) contain lacustrine rocks, contrasting sharply with the generally marine-dominated Cretaceous basins outside of China. In addition, the majority of these basins, except for the Songliao and Subei basins, mainly developed source rocks during the Early Cretaceous. Spatially, these Cretaceous basins can be divided into four oil and gas zones based on location, sedimentary environment, and tectonics (Dai et al, 1997; Tao, 2001; Fig. 2). These four zones are:

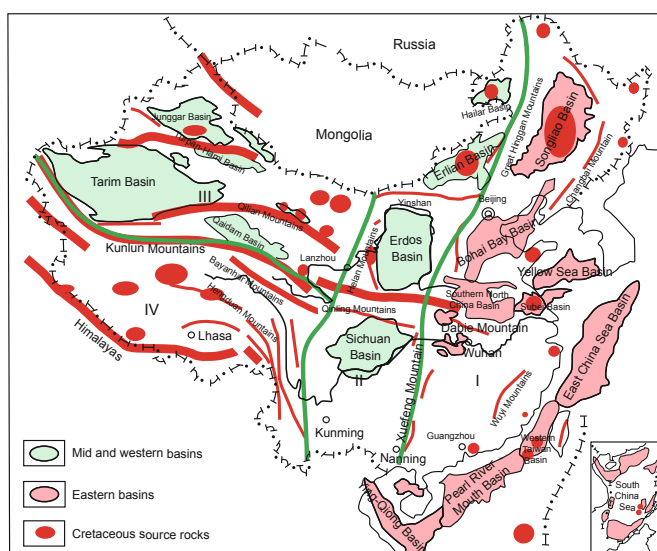


Fig. 2 The four Chinese oil and gas zones; modified after Dai et al (1997) and Tao (2001). I = Eastern stretching zone of Rift Valley, II = Central tectonic zone of stable craton, III = Northwestern tectonic zone of inversion, IV = Tethyan collision–strike-slip zone. Size of the red points indicates the scale and significance of the Cretaceous source rocks

3.1 Eastern stretching zone of the Rift Valley of China

The eastern stretching zone of Rift Valley lies to the east

of the Great Hinggan–Taihang–Wuling Tectonic Belt, and was deposited in a rift environment during the Mesozoic and Cenozoic (Tao, 2001). Basins hosting Cretaceous source rocks in this zone include the Songliao Basin and its peripheral basins, the Jiaolai, Subei, Yiyang, western Taiwan, southwestern Taiwan, and Lile basins, and the coastal area of southeastern China (Tables 4–6). This zone has undergone widespread Late Jurassic–Early Cretaceous volcanism, and subsequently experienced wide transgression during the Middle–Late Cretaceous (Fu et al, 2008; Xie et al, 2010; Jia et al, 2013). Lower Cretaceous source rocks

contain type II kerogen and are located in all basins within this zone. The majority of source rocks in the north of this zone are carbonaceous mudstones and mudstones, whereas source rocks in the south of this zone consist of dark mudstones, although the quality of source rocks in the south is much lower than that in the north (Xu et al, 2008). Upper Cretaceous source rocks have only been identified in the Songliao and Subei basins; however, these source rocks are characterized by extremely high quality, containing both type I and II kerogens; such source rocks are the main source of the hydrocarbons within this zone.

Table 4 Source rocks within the Songliao Basin of northeastern China (after Li et al, 2006; Sun et al, 2008)

Sag	Xujiaweizi	Xujiaweizi	Xujiaweizi	Changling	Changling	Changling	Changling	Changling	Changling
Period	K ₁	K ₁	K ₁	K ₂	K ₂	K ₂	K ₂	K ₂	K ₂
Formation	Shahezi	Yingcheng	Denglouku	First Member of the Qingshankou	Second and Third members of the Qingshankou	First Member of the Nenjiang	Second Member of the Nenjiang	Third Member of the Nenjiang	Fourth Member of the Nenjiang
Lithology	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone
Sedimentary facies	Shore shallow lacustrine	Shore shallow lacustrine	Shore shallow lacustrine	Lacustrine transgression	Shallow lacustrine	Lacustrine transgression	Shallow lacustrine	Shallow lacustrine	Delta
TOC, %	1.59	1.25	0.6	1.57	0.91	2.02	1.66	0.91	0.59
Kerogen type	III	III	III	I, II ₁	II ₁ , II ₂	I, II ₁	II ₁ , I	II ₁ , II ₂	III, II ₂
R _o , %	1.27-3.56	1.36-2.8	1.67-2.37	0.5-0.8	0.45-0.55	0.5-0.8	0.45-0.55	0.45-0.55	0.4-0.8

Table 5 Source rocks within peripheral basins around the Songliao Basin of northeastern China (after Fan et al, 2007; Su et al, 2008; Yu et al, 2008; Hou et al, 2009; 2010)

Basin	Songnan-Liaoxi	Songnan-Liaoxi	Jixi	Sanjiang	Sanjiang	Shuangyashan	Shuangyashan	Dunhua
Period	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁
Formation	Jiufotang	Shahai	Lower Cretaceous	Chengzihe	Muleng	Chengzihe	Muleng	Lower Cretaceous
Lithology	Carbonaceous mudstone	Mudstone, oil shale	Mudstone	Carbonaceous mudstone	Carbonaceous mudstone	Carbonaceous mudstone	Carbonaceous mudstone	Mudstone
Sedimentary facies	Shore shallow lacustrine	Shore shallow lacustrine	Shore shallow lacustrine	Shore shallow lacustrine	Transitional	Transitional	Transitional	Shore lacustrine to swamp
TOC, %	17.83-54.53	1.16-1.81	1.52	1.65	1.54	1.62	1.4	3.88
Kerogen type	III	III	III	III	III	III	III	III
R _o , %	0.46-0.66	0.67-0.70	0.5-1.1	0.5-2.0	0.5-2.0	0.79-0.86	0.76-0.83	0.47-0.59

Table 6 Source rocks within Eastern Zone basins of China in addition to the Songliao and its peripheral basins (after Zhou, 2000; Ren and Zha, 2003; Zhai et al, 2003; Xia et al, 2004; Chen et al, 2008; Hu et al, 2011a)

Basin	Jiaolai	Jiaolai	Subei	Yiyang	Southeastern China	Southeastern China	Southeastern China	Western Taiwan	Southwestern Taiwan	Lile
Period	K ₁	K ₁	K ₂	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁
Formation	Xiaoxianzhuang	Shuinan	Taizhou	Lengshuiwu	Bantou	Guantou	Shuidishan	Lower Cretaceous	Lower Cretaceous	Lower Cretaceous
Lithology	Shale	Shale, muddy dolomite	Mudstone, limestone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone
Sedimentary facies	Brackish lacustrine	Brackish lacustrine	Lacustrine	Lacustrine	Lacustrine transgression	Lacustrine transgression	Lacustrine transgression	Marine	Marine	Marine
TOC, %	0.67	0.81-2.14	1.54-2.32	0.94	0.92-1.24	0.61	1.24	0.6-0.8	0.5-1.0	0.3-0.8
Kerogen type	II ₁	I	I, II ₁	I, II	III	III	III, II ₁	III	III	III
R _o , %	1.4	0.71-0.83	0.5-0.8	0.50-1.18	0.5-2.0	0.5-2.0	0.5-1.3	0.98-1.22	0.6-1.0	/

Note: “/” denotes no data available

3.2 Central tectonic zone of the stable craton

The central tectonic zone of the stable craton lies between the Great Hinggan–Taihang–Wuling and Helan–Longmen tectonic belts and contains two famous and large petroliferous basins (i.e., the Ordos and Sichuan basins). The tectonic environment within this zone was relatively stable during the Mesozoic, and did not undergo any significant formation of

deep-rooted faults (Tao, 2001). The majority of Cretaceous source rocks within this zone were deposited in lacustrine environments of the depression and rift basins, such as the Hailar, Erlian, and Liupanshan basins. These Cretaceous source rocks contain type II and III kerogens, and are characterized by self-generating and -preserving petroleum systems (Lu et al, 2012) (Table 7).

Table 7 Cretaceous source rocks within the central tectonic zone of the stable craton, China (after Fang et al, 1998; Hao et al, 2006; He et al, 2007; Li et al, 2011)

Basin	Hailar	Hailar	Hailar	Erlian	Liupanshan	Liupanshan	Liupanshan
Period	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁
Formation	First Member of the Nantun	Second Member of the Nantun	Damoguaihe	Bayanhua	Naijiahe	Madongshan	Liwaxia
Lithology	Mudstone, sandstone	Mudstone, sandstone	Mudstone, sandstone	Mudstone	Limestone, shale	Limestone, shale	Mudstone, sandstone
Sedimentary facies	Lacustrine	Lacustrine	Lacustrine	Lacustrine	Shore shallow lacustrine	Lacustrine	Shore shallow lacustrine
TOC, %	1.86	1.73	1.66	1.36-2.77	1.71	1.58	0.55
Kerogen type	II ₁ , II ₂	II ₂ , III	III	II ₁ , II ₂	II ₁ , II ₂	II ₁ , II ₂	II ₂
R _o , %	0.72	0.61	0.55	<0.8	0.56-0.66	0.62-0.75	0.93-1.46

3.3 Northwestern tectonic zone of inversion

The northwestern tectonic zone of inversion lies to the north of the tectonic belt of West Qinling–Kunlun Mountains and to the east of the Longmen Mountains, and contains the Tarim, Junggar, and Turpan–Hami basins, as well as several smaller basins. Major basins within this zone have all undergone tectonic inversion from compression to extension

(Tao, 2001). Cretaceous source rocks are present in the basins along the Hexi Corridor (including the western and eastern Jiuquan, Huahai, and Beishan basins), and in the Yin'e, Gonghe, and southern Junggar basins. All of these source rocks were deposited in lacustrine environments during the Early Cretaceous, and are dominated by type II kerogen, although some source rocks also contain type III kerogen (Tables 8 and 9).

Table 8 Cretaceous source rocks within the Hexi Corridor basins, China (after Liu and Jin, 2002; Ma and Cheng, 2012)

Basin	Huahai	Western Jiuquan	Western Jiuquan	Eastern Jiuquan	Eastern Jiuquan	Beishan	Beishan
Period	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁
Formation	Xinminbao	Chijinbao	Xinminbao	Chijinbao	Xinminbao	Xinminbao	Xinminbao
Lithology	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Carbonaceous mudstone
Sedimentary facies	Lacustrine	Shore shallow lacustrine	Lacustrine	Lacustrine	Lacustrine	Shore shallow lacustrine	Shore shallow lacustrine
TOC, %	2.43-5.9	1.24	1.41	0.6	1.0	1.52	9.57
Kerogen type	II ₁	III	II ₁ , II ₂	II ₂	II ₂ , III	III	III
R _o , %	/	0.7-0.9	0.6-0.8	1.0-1.3	0.7-1.2	0.76	0.44-0.76

Note: “/” denotes no data available

Table 9 Cretaceous source rocks within the basins of the northwestern zone of tectonic inversion in addition to the Hexi Corridor basins, China (after Meng et al, 1999; Wang et al, 2001; Abulimiti et al, 2004; Wu and Bai, 2006; Wei et al, 2008; Cao et al, 2010; Tu et al, 2012)

Basin	Southern Junggar	Gonghe	Gonghe	Gonghe	Yin'e	Yin'e
Period	K ₁	K ₁	K ₁	K ₁	K ₁	K ₁
Formation	Tugulu	Third Member of the Wanxiu	Second Member of the Wanxiu	First Member of the Wanxiu	Bayingebi	Suhongtu
Lithology	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone	Mudstone
Sedimentary facies	Lacustrine	Lacustrine	Lacustrine	Lacustrine	Lacustrine	Shore shallow lacustrine
TOC, %	0.72-1.45	0.40	1.34	0.36	0.63-1.98	0.89-1.39
Kerogen type	I, II ₁	II ₁ , II ₂	I	I, II ₁	II ₁ , II ₂	II ₂ , III
R _o , %	0.56-0.8	0.6-1.1	0.6-1.1	0.6-1.1	>0.8	0.5-0.8

3.4 Tethyan collision–strike-slip zone

The Tethyan collision–strike-slip zone lies to the south of the tectonic belt of West Qinling–Kunlun Mountains, and to the west of the Longmen Mountains, and occurs mainly on the Qinghai–Tibet Plateau. This zone was part of the Tethyan Ocean during the Mesozoic, an environment which commonly led to the deposition of marine source rocks. After this deposition, rapid Early Cenozoic uplift of the Qinghai–Tibet Plateau, caused by collision between the Indian and Eurasian plates, made this zone into a continental

setting. Basins in this zone are characterized by thickened crust, significant volcanism, and extremely high geothermal gradients (Tao, 2001). Cretaceous source rocks within this zone were generally formed in marine or transitional environments (Table 10), and are present in residual basins such as the Qiangtang, Cuoqin, Bolin, and Biru basins. The significant Cenozoic tectonic and volcanic activity in this area indicates that the majority of Cretaceous source rocks are of poor quality, although some basins preserve high-quality ones.

Table 10 Cretaceous source rocks within the Tethyan collision–strike-slip zone, China (after Cheng et al, 2000; Li et al, 2010; Liu, 2010; Wang et al, 2010; Wei et al, 2011)

Basin	Bolin	Bolin	Cuoqin	Cuoqin	Biru	Qiangtang
Period	K _{1,2}	K ₂	K ₁	K ₁	K ₁	K ₁
Formation	Gamba	Langshan	Duoni	Langshan	Duoni	The Upper Member of Suowa
Lithology	Shale	Limestone	Carbonaceous shale	Limestone	Mudstone	Oil shale
Sedimentary facies	Shelf	Shelf	Transitional	Carbonate platform	Transitional	Marine
TOC, %	0.7-1.08	0.03-0.05	7.34	0.01-0.1	0.71	9.76
Kerogen type	II ₁	II ₁	II ₁ , II ₂	I, II ₁	II, III	II ₁ , II ₂
R _o , %	1.20-1.24	1.28-1.65	1.3-2.5	1-1.3	1.85-2.59	0.37-0.90

In summary, Cretaceous petroliferous basins in China are predominantly relatively small-scale lacustrine basins. The marine basins are only located on the Qinghai–Tibet Plateau and offshore of eastern China. The majority of these Cretaceous source rocks were developed in the Lower Cretaceous, and Upper Cretaceous source rocks are only found in the Songliao, Subei, and Bolin basins. In the Eastern Zone basins, the Lower Cretaceous source rocks mainly contain type III kerogen, whereas the Upper Cretaceous source rocks mainly contain type II kerogen. With respect to central, northwestern, and Qinghai–Tibet Plateau areas, type II kerogen dominates in the Cretaceous source rocks. In terms of source–reservoir–cap rock combinations, Cretaceous source rocks are dominantly dark mudstones and shales that are associated with sandstone and mudstone/shale as reservoir and cap rocks respectively. Note that the reservoir rocks also include minor carbonate (e.g., the Qinghai–Tibet Plateau; Wei et al, 2011) and igneous rocks (e.g., the Songliao Basin; Huang et al, 2010; Zou et al, 2010; Cai et al, 2012). It is characterized by a self-generating and -preserving assemblage, with some being combined with adjacent clastic rocks.

4 Formation models and controls of Cretaceous source rocks

4.1 Formation models of Cretaceous source rocks

The above review of the location and basic petroleum-system geology of global and Chinese Cretaceous source rocks indicates that these rocks have four different types of

formation models.

1) Global sea-level rises and OAEs (Fig. 3(a))

This formation model can be typically exemplified by the La Luna Formation of the Maracaibo Basin and the Kazhumi Group of the Zagros Basin. Frequent volcanic activity and strong greenhouse effects lead to strong weathering and large amount of input of nutrients into sea water. High temperatures at low latitudes caused highly oxygenated surface ocean waters to become overpopulated with algae which consumed large amounts of oxygen. As a consequence, contemporaneous anoxia occurred in the deep ocean. This anoxia ensured that planktons remain undecomposed, leading to the formation of sea snow and preservation in reducing deep-ocean environments. Under this model, a mass of high-quality source rocks was formed, and thus this becomes one of the most important models of the formation of Cretaceous source rocks worldwide. This sedimentary pattern can be identified by the following three main features: (i) source rocks developed in continental slope and ocean bottom settings; (ii) very thick anoxic sedimentary layers at the base of the sedimentary package; and (iii) the source of organic matter dominated by oceanic algae.

2) Black Sea retention basins (Fig. 3(b))

This setting can be typically exemplified by the Guaratiba Formation of the Santos Basin in the South Atlantic, developed mainly within semi-restricted lagoons. The stagnation of water in this environment leads to a separation of surface and deep waters, with surface waters undergoing significant evaporation and oxidation, whereas the deep waters increase in salinity and become reducing. These environmental factors are favorable for the preservation of

organic matter. Source rocks formed in this environment contain a high abundance of organic matter, type I and II kerogens, significant amounts of sulfur, and a brackish-water algae assemblage that hosts little benthic organic matter. This type of source rock commonly has relatively limited scale spatially due to strict requirements of the sedimentary environment.

3) Transgressive settings (Fig. 3(c))

This formation pattern of Cretaceous source rocks can be typically exemplified by the Hue Shale of the Alaskan North Slope Basin, and similar patterns were also found in the Rocky Mountains foreland basin, the Cretaceous Qingshankou and Nenjiang formations of the Songliao Basin, the Taizhou Formation of the Subei Basin, and the Lower Cretaceous of coastal southeastern China. This setting is characterized by organic matter derived from both terrestrial and oceanic areas from geographically opposite directions. The distribution of source rocks is transitional with changes from land to sea, including fan delta, lacustrine, fresh-brackish tidal flat and marine facies. Source rocks closer to terrestrial areas have more humic compositions in kerogens.

4) Terrestrial input (Fig. 3(d))

This formation pattern of Cretaceous source rocks can be typically exemplified by continental basins, such as the Lower Cretaceous of the Lower Congo Basin of the South Atlantic, and the fourth Member of the Nenjiang Formation of the Songliao Basin. Along with the different developmental stages of a lake, source rocks can be formed in different facies, including delta, shore and shallow lake, and deep lake facies. The source of the organic matter ranges from terrestrial higher plants to lower aquatic biologies. The distribution scale is commonly relatively limited due to a continental setting in general.

4.2 Controls of the formation of Cretaceous source rocks

Source rock formation is generally dependent on two main factors, the development of hydrocarbon bioprecursors and their preservation, which is further controlled by multiple factors, e.g., paleoclimate, paleoceanography, paleotectonics, and paleoenvironment (Li et al, 2008). Based on the review of Cretaceous source rocks in this article, we believe that the formation of Cretaceous source rocks, both in China and globally, was controlled by the following four main geological factors.

1) Paleoclimate

Paleoclimatic conditions are an important control on both kerogen type and the deposition rate of organic matter, and therefore have an impact on the type and distribution of source rocks. For example, terrestrial plants generally thrive in warm environments, whereas bacteria can more readily adapt to temperature changes. Arid climates are likely to cause partial oxidation of evaporites and red beds, whereas humid climates are more conducive to the deposition of organic matter.

The Cretaceous climate is usually believed to have been dominated by greenhouse conditions, as evidenced by widespread deposition of evaporite and terrestrial red beds, the formation of high-latitude forests, and a general lack of glaciers (Jenkyns, 2010; Moriya, 2011; Wang et al, 2011; Föllmi, 2012; Hu et al, 2012c). Foraminiferal oxygen isotope data indicate that the average temperature in the Cretaceous was 10 °C higher than the present (Friedrich et al, 2012; Jenkyns et al, 2012). For instance, the average annual temperature in Alaska of the USA is currently -5 °C, whereas it was shown to be higher than 5 °C in the Cretaceous from the reconstruction of vegetation types and the morphological

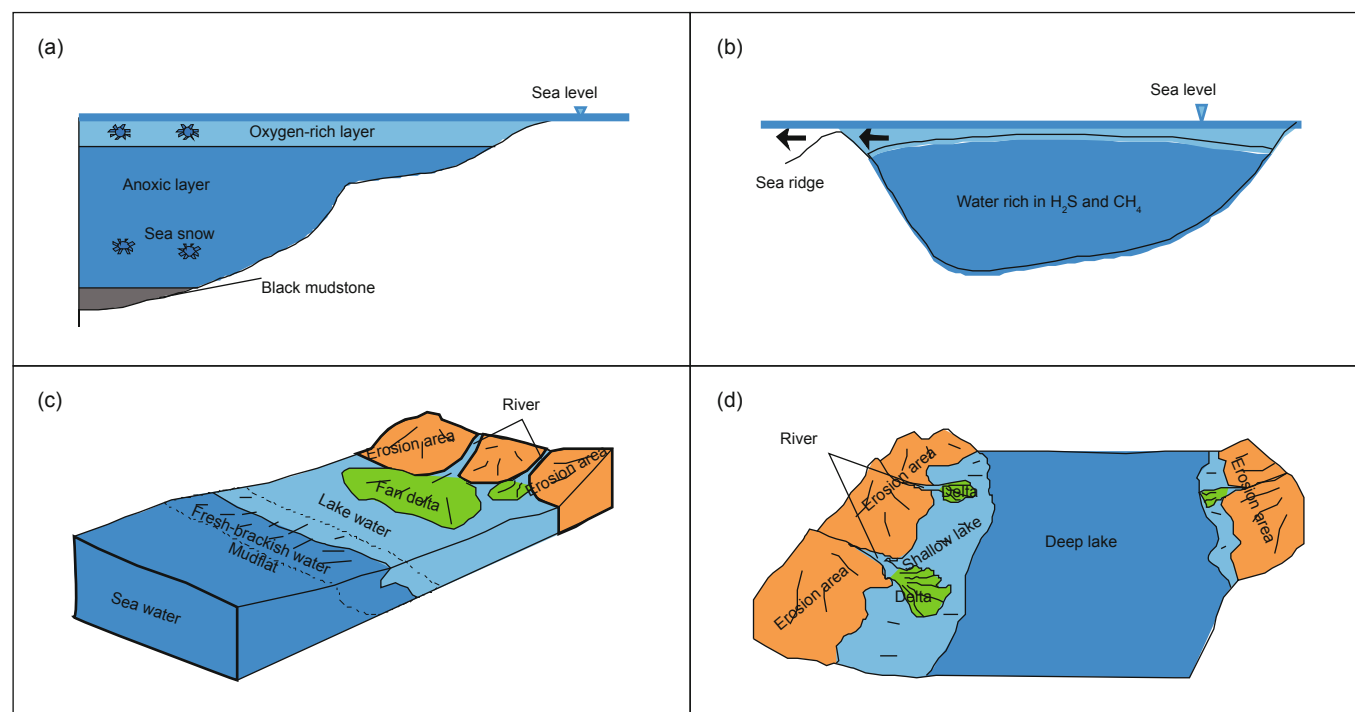


Fig. 3 Generalized four formation models of Cretaceous source rocks. (a) global sea-level rises and OAEs, (b) Black Sea retention basins, (c) transgressive settings, (d) terrestrial input

research on angiosperm leaves, especially leaf edge characteristics. Moreover, a significant amount of coal is present in northern Alaska, confirming the presence of huge high-latitude forests during the Cretaceous. Paleomagnetic data for this area indicate that it was located at latitudes of 75°N–85°N during the Cretaceous, further implying that the climate at that time was much warmer and wetter than today (Spicer and Herman, 2010). This climatic condition is favorable for the development of abundant organic matter in the high-latitude Boreal Realm, which was generally deposited in lacustrine (e.g., Western Siberia) or foreland (e.g., North Slope and Western Canada) basins, in turn suggesting a continent-dominated sedimentary regime, and explaining why the majority of the Cretaceous source rocks in this realm dominantly contain type III kerogen.

In contrast to the high-latitude areas discussed above, the low-latitude areas were also influenced by the greenhouse climate regime, as exemplified by extremely thick carbonate units within the mid-latitude Tethys (Fig. 4; Skelton, 2003). These reefs are produced from bivalve biologies, which are represented by a type of extinct rudist; which has only been reported during this period (Skelton et al, 2011; 2013). Large number of these organisms was found in the Persian Gulf–Zagros Basin source rocks, namely the Kazhkumi and Natih formations (Droste, 2010; Rahmani et al, 2010).

2) Paleotopography

Paleotopography (i.e., the geomorphological location) of a basin determines the source of organic matter, and controls the sedimentary environments in combination with climate. Large petroliferous basins are generally developed in shelf areas and within large lacustrine environments, areas that have significant sources of organic matter (Liu et al, 2011; Deng, 2012). Basins that host Cretaceous source rocks are generally located in modern coastal and continental shelf environments,

which are similar to those during the Cretaceous. Thus, it can be implied that the tectonic setting has not changed significantly since the Cretaceous. In contrast, semi-restricted lagoons generally lead to the formation of reducing environments that are conducive to the preservation of organic matter. Open shallow waters commonly have significant sources of organic matter; however, the relatively oxidizing environment prevalent in these areas is not favorable for the development of good-quality source rock with type I and II kerogens.

The largest tectonic event that occurred during the Cretaceous and has important impacts on the source rock formation was the separation of South America from Africa and the formation of the South Atlantic. This led to the formation of three different types of source rocks within South Atlantic basins. The first type was developed during rifting or transitional periods, and was deposited in lacustrine, deltaic environments as shales and mudstones containing type II or III kerogens, such as in the Bucumazi Formation of the Congo Basin. The second type was developed during transitional periods as sediments within semi-restricted environments with saline or brackish water, forming shales that contain type I and II kerogens, such as in the Guaratiba Formation of the Santos Basin. The third type was generally developed during Late Cretaceous drifting; these source rocks are generally shales that formed in marine environments and contain either type II (deep water) or type III (shallow water) kerogens, as typically exemplified by the Itajai–Açu Formation of the Santos Basin (He et al, 2011; Beglinger et al, 2012).

3) Transgression

Several global transgressions occurred during the Cretaceous, such as (i) the Early Cretaceous Aptian transgression in the southeastern coast of China (Xie

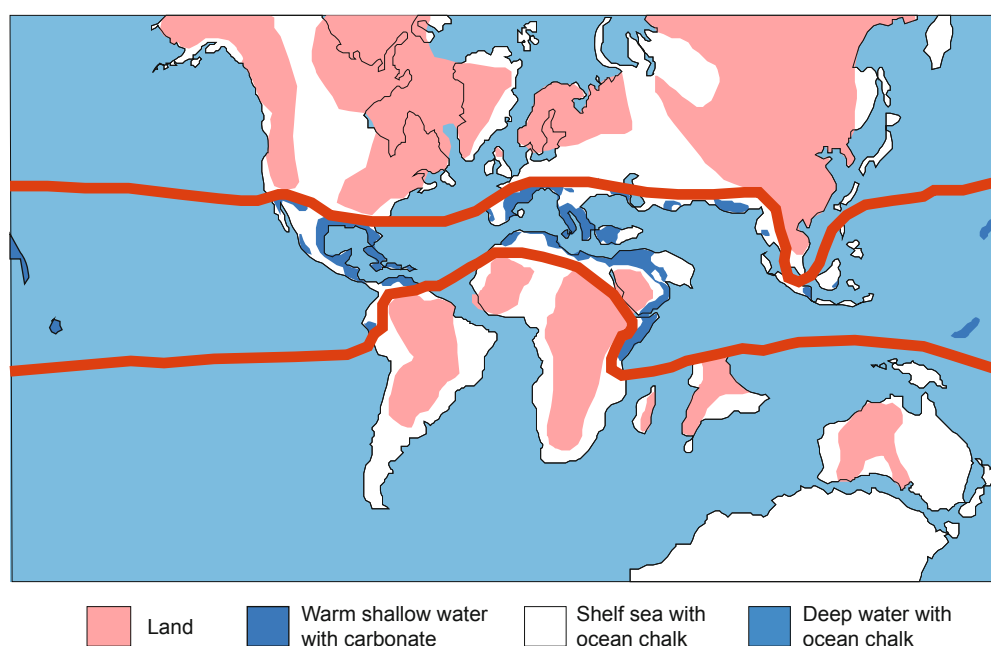


Fig. 4 Reconstruction of paleogeography in the Cretaceous Cenomanian stage. The area between the red lines shows the distribution of carbonate platforms (Skelton, 2003)

et al, 2010; Hu et al, 2012a), South Atlantic rift basins (Aguirre-Urreta et al, 2011), and Mexico Gulf Coast Basin (Moreno-Bedmar et al, 2012); (ii) the Late Cretaceous Cenomanian transgression across the entire continental North America (Gao et al, 2011) and in the Songliao Basin of China (Jia et al, 2013); and (iii) the Late Cretaceous Turonian–Campanian transgression in the Libyan Sirt Basin (Tian et al, 2008) and in the Subei and Songliao basins of China (Fu et al, 2008). These transgressions led to the formation of a series of high-quality source rocks, such as the Colorado Group in the Alberta Basin of West Canada, and the Qingshankou and Nenjiang formations of the Songliao Basin of northeastern China. They changed the source and abundance of organic matter and the depositional environment within the sedimentary basins. In particular, the kerogen type of the organic matter was improved from humic to dominantly sapropelic. This is shown by the difference between type II kerogen of the Colorado Group and the type III kerogen of the Lower Cretaceous Mannville Group in the Rocky Mountains foreland basin. In addition, the First Member of the Qingshankou Formation and the First Member of the Nenjiang Formation within the Songliao Basin that were influenced by transgressions have higher-quality source rocks than adjacent sediments that were not influenced by transgressions.

4) Oceanic Anoxic Events

The low amount of dissolved oxygen in Cretaceous seawater caused a significant number of black shale deposition events, termed Oceanic Anoxic Events (OAEs). Six such events are: OAE1a in the Early Aptian, OAE1b in the Late Aptian, OAE1c in the Middle Albian, OAE1d in the Late Albian, OAE2 in the Late Cenomanian, and OAE3 in the Late Coniacian. These events are recorded by the presence of widespread marine black shale units within oceanic and continental settings (Huang et al, 2008; Wagreich et al, 2011). Many of the world's largest petroliferous basins are associated with black shales that formed during OAEs, including the Kazhkumi Formation of the Persian Gulf–Zagros Basin that was formed during OAE1d (Bai, 2007), the Sirt Shale that was formed during OAE2, the Eagle Ford Shale of the US Gulf Coast that was formed during OAE2 (Robison, 1997; Schieber, 2011), the La Luna Formation of the Maracaibo Basin that was formed during OAE3 (Wagreich, 2012), and the Qingshankou and Nenjiang formations of the Songliao Basin that were formed during OAE2 and OAE3, respectively (Wu et al, 2008). The deficiency of dissolved oxygen in seawater can cause a reduction in microbial decomposition, and is conducive to the deposition of organic matter. The presence of anoxic water from a reducing environment is also conducive to the development of sapropelic kerogens.

5 Future targets for Cretaceous oil and gas exploration in China

Based on the above discussion, China should be favorable for Cretaceous oil and gas exploration (e.g., the successful Songliao Basin) being located in the Tethyan and Boreal realms during the Cretaceous. Considering the relatively

underexplored areas, we suggest two high-priority exploration targets, including the Qinghai–Tibet Plateau and the coastal southeastern China. They have relatively good conditions in terms of the above four factors that control Cretaceous source rock formation.

5.1 Qinghai–Tibet Plateau

The Qinghai–Tibet Plateau is the area that likely has the lowest level of hydrocarbon exploration within onshore China (Yu et al, 2009; Fu et al, 2010; Li et al, 2010; Ding et al, 2011). This area was part of the Tethyan Ocean during the Mesozoic and contains abundant marine sediments (Nan et al, 2012; Wang et al, 2012b). After the Mesozoic, a number of marine and transitional residual basins were developed, including the Qiangtang, Cuoqin, Biru, and Bolin basins. Hydrocarbon shows have been found in the first three (Cheng et al, 2000; Li et al, 2010; Wang et al, 2012b). Even in the Bolin Basin, adjacent areas have been documented with hydrocarbon shows, including the Gamba area of Tibet and the Mustang area of Nepal (Wang et al, 2010). This indicates that all of these basins, including the Bolin Basin, have the potential to produce oil and gas.

The main Cretaceous source rocks within the Qiangtang Basin are marine oil shales within the Lower Cretaceous as well as the Upper Jurassic. These source rocks were first discovered along the west bank of the Shengli River, and thus are termed the Shengli River Oil Shale. The shale extends in a WNW–ESE direction, with an area of approximately 80 km (east to west) × 30 km (north to south). It is dominantly of low maturity, contains type II kerogen, and is overlain by gypsum caprock (Fu et al, 2010; Li et al, 2010).

The main source rocks within the Cuoqin Basin are the Lower Cretaceous Doni and Langshan formations. Doni Formation source rocks were deposited in a deltaic environment, leading to the formation of carbonaceous shales that contain highly-mature type II kerogen. This indicates that these source rocks may only have gas potential. In comparison, the Langshan Formation source rocks consist of limestones deposited on a carbonate platform. These rocks generally contain low organic matter abundance, are highly mature, and contain type I and II kerogens. However, some source rocks with relatively high total organic carbon (TOC) content (>2%) have been documented, meaning that this formation may be the main source rock within the basin. The main reservoirs are sandstones and bioclastic limestones of the Doni Formation, and dolomite and reef limestones of the Langshan Formation. These reservoirs are associated with mudstone and micrite cap rocks, forming self-generating and -preserving petroleum systems (Wei et al, 2011).

This set of Doni Formation source rocks is also present in the Biru Basin. The rocks were deposited in a deltaic environment, are highly mature, and contain type II and III kerogens, indicating that these source rocks may only have gas potential. Reservoirs and cap rocks are sandstones and shales, respectively, again indicative of a self-generating and -preserving petroleum system (Liu, 2010).

With respect to the Bolin Basin, Aptian Gamba Group black shales are the major source rocks. These shales were

deposited in a shallow continental shelf environment, contain high concentrations of TOC and type II kerogen, and have an intermediate maturity indicative of high-quality source rocks. In contrast, Zongsain Formation limestones contain very low TOC concentrations, indicating that this unit is only a minor source rock within the basin. The Bolin Basin reservoir is sandstones within the Gamba Group. These rocks are associated with mudstone cap rocks within the same group, and marlstone and micrite cap rocks of the overlying Zongshan Formation, further indicating that the Bolin Basin petroleum system is a self-generating and -preserving system.

5.2 Coastal southeastern China

Coastal southeastern China, including the areas around Guangdong, Fujian, Zhejiang, and Taiwan provinces, underwent significant Late Jurassic–Early Cretaceous volcanism that peaked in the Early Cretaceous, forming a thick volcano-sedimentary sequence. Later tectonism, termed the Minzhe Movement, led to the formation of a number of faulted basins due to a change of tectonic setting from compression to extension (Chen et al, 2009; Shu et al, 2009). As a consequence, deep-lake lacustrine dark mudstones were formed. They are the main source rocks in coastal southeastern China during the Early Cretaceous (Hu et al, 2011a). These areas remain relatively unexplored, with only a few hydrocarbon shows being documented. Source rocks within this area can be divided into two periods, including (i) the early stage of the Early Cretaceous, associated with the formation of the Shuidishan Formation in Guangdong Province, and the basal section of the Bantou Formation in Fujian Province; and (ii) the late stage of the Early Cretaceous, associated with the formation of the Guantou Formation in Zhejiang Province and the upper parts of the Bantou Formation (Hu et al, 2011b; 2012a; 2012b; Wang et al, 2012a). The excessively high level of thermal evolution of source rocks in this region, combined with the dominance of type III kerogen, indicates that these source rocks may now only have gas potential. In addition, these source rocks were influenced by Early Cretaceous transgressions to varying degrees. The thicknesses and proportions of transgressive sediments increase from northwest to southeast, indicating that the transgression occurred from the east of this area (Hu et al, 2012a). As such, it can be speculated that the areas to the east of the southeastern coast of China, such as the East China Sea and the northern South China Sea, should contain high-quality Early Cretaceous source rocks that may have certain hydrocarbon (oil) generation potential (Zhang, 2012).

The western and southwestern Taiwan Basin and the Lile Basin are adjacent to coastal southeastern China, being located in the eastern margin of the Tethyan Realm and to the north of the South China Sea. This area contains coastal–deltaic clastic sediments in general. In addition, the western Taiwan Basin contains marine mudstones and deltaic coal-bearing sediments. In the southwestern Taiwan Basin, wells CFC-1, -2, and -3 and well A1-B intercepted deltaic sandstones, mudstones, and shales, and wells Sampaguita-1 and Rea Bank A1 within the Lile Basin intercepted consolidated

sandstones and shales that contain thin seams of brown coal sequences. These lithologies are indicative of deposition in a coastal deltaic sedimentary environment (Xia et al, 2004). The rocks mainly contain type III kerogen, indicative of gas potential.

Some oil and gas resources have been produced onshore within the western and southwestern Taiwan Basin, as typically exemplified by the presence of 15 small oil and gas fields within the western Taiwan Basin. In comparison, offshore production is mainly from units that overlie Cretaceous strata, as shown by 1.5×10^6 m³/d gas production from Oligocene sediments in the southwestern Taiwan Basin, and production of 1.5×10^6 m³/d gas and 115–125 bbl/d condensate from Eocene sediments within the Lile Basin (Xia et al, 2004).

There are generally two types of source–reservoir–cap rock combinations in this area, i.e., a self-generating and -preserving petroleum system, and a system that consists of Cretaceous shale and mudstone source rocks, Tertiary sandstone reservoirs, and Tertiary shale and mudstone cap rocks. They are favorable targets for hydrocarbon exploration in the future.

6 Conclusions

1) Occurrence of Cretaceous source rocks and associated oil and gas resources worldwide can be divided into four realms, i.e., Tethyan, Boreal, South Gondwana, and Pacific. The Tethyan Realm contains the majority of oil and gas resources within these four realms, e.g., the Persian Gulf, the Mediterranean, the US Gulf Coast, and other regions. The majority of basins within the Tethyan Realm are marine, and have carbonate and shale source rocks that contain predominantly type II kerogen. These source rocks are often found in source–reservoir–cap rock combinations with carbonate reservoirs and gypsum or mudstone being cap rocks. In contrast, Boreal Realm basins are mostly lacustrine or foreland basins associated with source rocks containing type III kerogen. These basins contain mudstone, shale, and a small number of coal-bearing source rocks, sandstone reservoirs, and mudstone and shale cap rocks. South Gondwana Realm basins have characteristics similar to both the Tethyan and Boreal realms. The Pacific Realm has the least hydrocarbon resources.

2) Cretaceous source rocks in China were generally formed during the Lower Cretaceous. However, Upper Cretaceous high-quality source rocks have been identified with transgressive influences. Spatially, the source rocks can be divided into four zones, including the eastern stretching zone of the Chinese rift valley, the central tectonic zone of the stable craton, the northwestern tectonic zone of inversion, and the Tethyan collision–strike-slip zone. Of the four zones, the Qinghai–Tibet area is the only one that has marine source sequences. The other regions are continental in nature, with likely influences of transgression. Lower Cretaceous Eastern Zone basins mainly contain type III kerogen, whereas Upper Cretaceous basins mainly contain type I and II kerogens. In the central, northwestern, and Qinghai–Tibet Plateau areas,

type II kerogen dominates. In terms of source–reservoir–cap rock combinations, Cretaceous source rocks are dominantly dark mudstones and shales, reservoir rocks are mainly sandstones with some carbonates and igneous rocks, and cap rocks are mainly mudstones and shales. It is generally a self-generating and -preserving assemblage, with some being combined with adjacent clastic rocks.

3) Formation of Cretaceous source rocks have four models in general: i) during global sea-level rises and Oceanic Anoxic Events, ii) within a Black Sea retention basin setting, iii) during transgression, and iv) associated with terrestrial input. The formation and distribution is controlled by four main factors: paleoclimate, paleotopography, transgression, and Oceanic Anoxic Events.

4) Cretaceous source rocks in China are at a relatively early stage of exploration except for those within the Songliao Basin and its associated peripheral basins. Of the under-explored areas, the Qinghai–Tibet Plateau and coastal southeastern China are especially the areas that may have relatively good hydrocarbon prospects. They have the favorable combination of the four formation controls of Cretaceous source rocks, implying that these areas should be high-priority exploration targets.

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