DOI 10.1007/s12182-014-0348-z

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

**Yang Ruofei[1], Wang Yuce[2] and Cao Jian[1]***

[1] State Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing, Jiangsu 210023, China

[2] School of Petroleum Engineering, China University of Petroleum, Qingdao, Shandong 266580, China

© China University of Petroleum (Beijing) and Springer-Verlag Berlin Heidelberg 2014

**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

*Corresponding author. email: jcao@nju.edu.cn
Received May 12, 2013

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

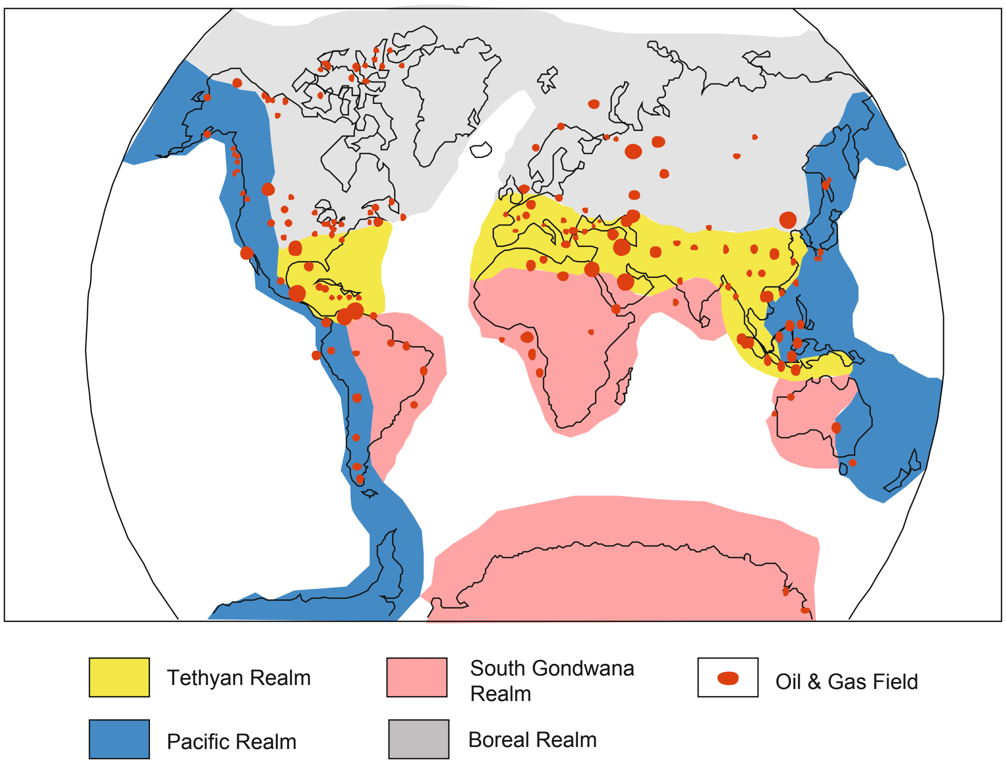


**Fig. 1** The four global oil and gas realms (modified after Klemme and Ulmishek, 1991). Size of the red points indicates the scale and significance of the oil/gas field

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:

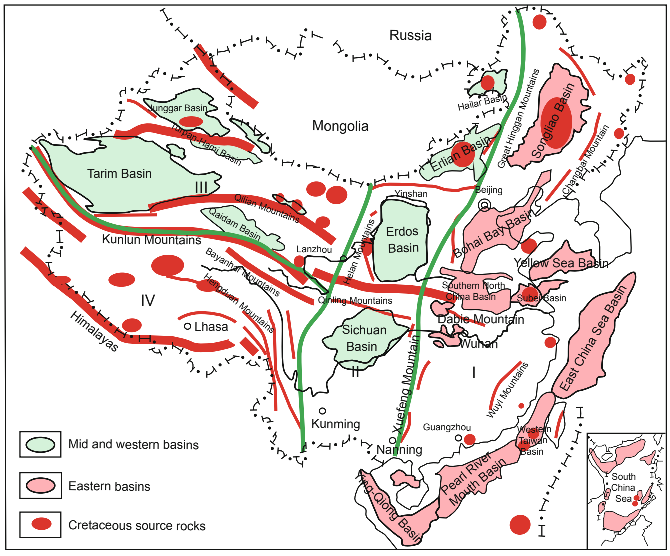


**Fig. 2** The four Chinese oil and gas zones; modified after Dai et al (1997) and Tao (2001). I = Eastern stretching zone of Rift Valley, II = Central tectonic zone of stable craton, III = Northwestern tectonic zone of inversion, IV = Tethyan collision–strike-slip zone. Size of the red points indicates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

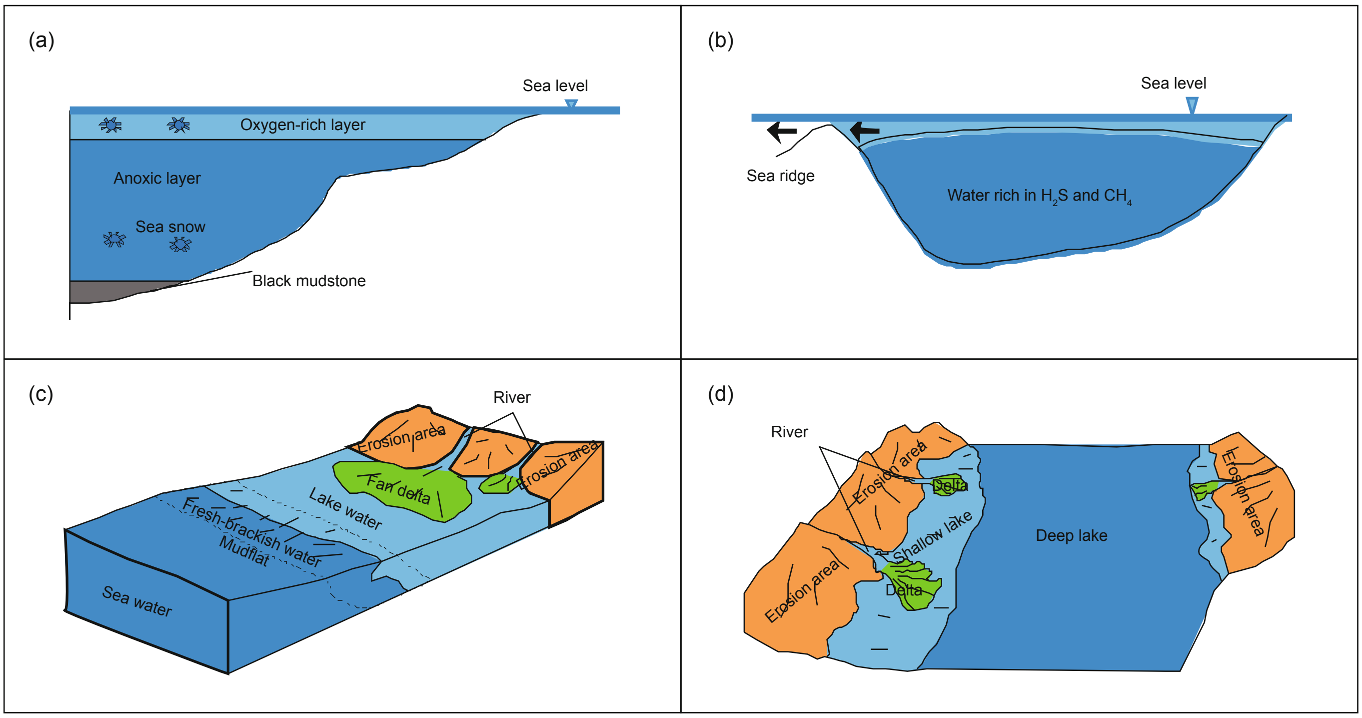


**Fig. 3** Generalized four formation models of Cretaceous source rocks. (a) global sea-level rises and OAEs, (b) Black Sea retention basins, (c) transgressive settings, (d) terrestrial input

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 Bucomazi 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–Acu 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

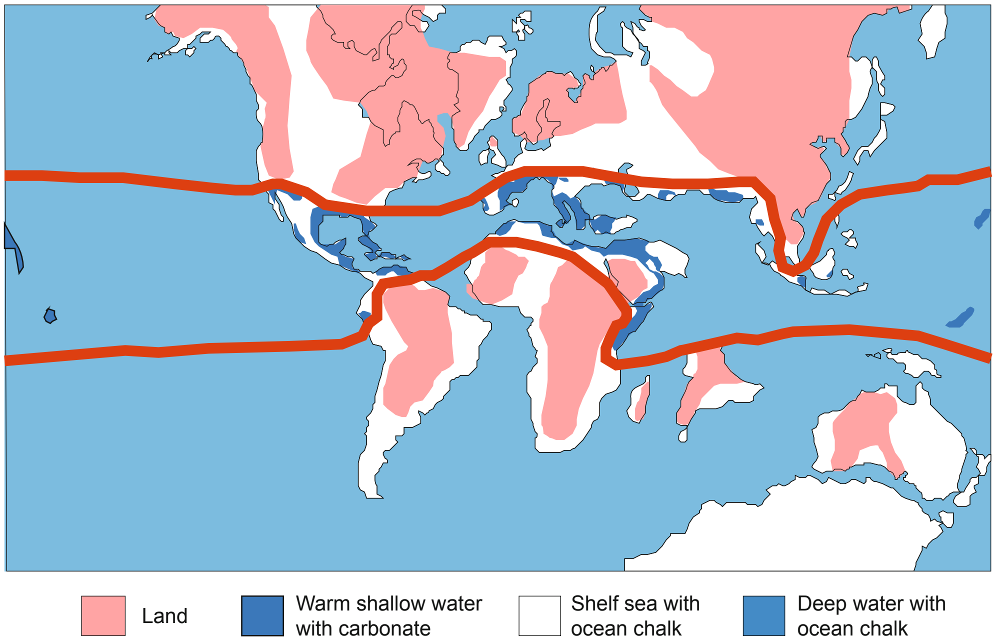


**Fig. 4** Reconstruction of paleogeography in the Cretaceous Cenomanian stage.
The area between the red lines shows the distribution of carbonate platforms (Skelton, 2003)

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 Reea 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 $1.5 \times 10^6$ $m^3/d$ gas production from Oligocene sediments in the southwestern Taiwan Basin, and production of $1.5 \times 10^6$ $m^3/d$ 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.

## Acknowledgements

We thank two anonymous reviewers for their constructive reviews. This work was supported by the Major State Basic Research Development Program (973 project, Grant No. 2012CB214803) and National Natural Science Foundation of China (Grant No. 41322017).

## References

Abulimiti, Tang Y, Li C, et al. New understandings of Cretaceous oil generation zone in foreland basin in southern margin of the Junggar Basin. Xinjiang Petroleum Geology. 2004. 25(4): 446-448 (in Chinese)

Aguirre-Urreta B, Tunik M, Naipauer M, et al. Malargüe Group (Maastrichtian–Danian) deposits in the Neuquén Andes, Argentina: Implications for the onset of the first Atlantic transgression related to Western Gondwana break-up. Gondwana Research. 2011. 19(2): 482-494

Alberdi-Genolet M and Tocco R. Trace metals and organic geochemistry of the Machiques Member (Aptian– Albian) and La Luna Formation (Cenomanian–Campanian), Venezuela. Chemical Geology. 1999. 160: 19-38

Aleksandrova G N, Kosmynin V A and Postnikov A V. Stratigraphy and sedimentary environments for Cretaceous deposits in the southern part of the Var'egansk Megabar (Western Siberia). Stratigraphy and Geological Correlation. 2010. 18(4): 411-435

Anders D E and Magoon L B. Oil-source correlation study in northeastern Alaska. Organic Geochemistry. 1986. 10: 407-415

Bai G P. Distribution patterns of giant carbonate fields in the world. Journal of Palaeogeography. 2006. 8(2): 241-250 (in Chinese)

Bai G P. A preliminary study of main control factors on oil and gas distribution in Persian Gulf Basin. Journal of China University of Petroleum (Edition of Natural Science). 2007. 31(3): 28-32, 38 (in Chinese)

Balbinot M and Kalkreuth W. Organic geochemistry and petrology of the Gomo Member, Recôncavo Basin, Brazil. International Journal of Coal Geology. 2010. 84: 286-292

Beglinger S E, Doust H and Cloetingh S. Relating petroleum system and play development to basin evolution: West African South Atlantic basins. Marine and Petroleum Geology. 2012. 30(1): 1-25

Cai Z R, Huang Q T, Xia B, et al. Development features of volcanic rocks of the Yingcheng Formation and their relationship with fault structure in the Xujiaweizi Fault Depression, Songliao Basin, China. Petroleum Science. 2012. 9(4): 436-443

Cao J, Wang X L, Wei D T, et al. Complex petroleum migration and accumulation in the central region of the southern Junggar Basin, northwest China. Journal of Earth Science. 2010. 21(1): 83-93

Chen A D, Song N and Wang W J. An evaluation of the source bed in Upper Cretaceous Taizhou Formation, Subei Basin. China Offshore Oil and Gas. 2008. 20(1): 28-33 (in Chinese)

Chen B, Zhang C M, Luo M X, et al. Hydrocarbon accumulation model of the Cretaceous in southern China. Science in China Series D: Earth Sciences. 2009. 52(1): 77-87

Cheng D S, Li Y T, Gang W Z, et al. Features of hydrocarbon sources of Cuoqin Basin in Northern Tibet. Xinjiang Petroleum Geology. 2000. 21(3): 180-183 (in Chinese)

Creaney S and Sullivan M A. The genetic evolution of Arctic North America and Greenland and implications for petroleum systems. Geological Society, London. 2011. Memoirs 35(1): 451-462

Dai J X, Wang T B, Song Y, et al. Formation and Distribution of Medium-Large-size Gas Fields in China. Beijing: Geological Publishing House. 1997. 1-4 (in Chinese)

Deng Y H. River-gulf system—the major location of marine source rock formation. Petroleum Science. 2012. 9(3): 281-289

Ding W L, Li C, Su A G, et al. Study on the comprehensive geochemical cross section of Mesozoic marine source rocks and prediction of favorable hydrocarbon generation area in Qiangtang Basin, Tibet. Acta Petrologica Sinica. 2011. 27(3): 878-896 (in Chinese)

Droste H. High-resolution seismic stratigraphy of the Shu'aiba and Natih formations in the Sultanate of Oman: implications for Cretaceous epeiric carbonate platform systems. Geological Society, London, Special Publications. 2010. 329(1): 145-162

El-Alami M. Habitat of oil in Abu Attiffel area, Sirt Basin, Libya. In: Salem M J, et al (Ed), The Geology of Sirt Basin. 1996. 2: 337-348

Fan F, Gao F H and Gao H M. Genetic potential of coal-measure source rocks of Lower Cretaceous in Jixi Basin. Xinjiang Petroleum Geology. 2007. 28(1): 36-39 (in Chinese)

Fang J, Hou F X, Sun T T, et al. Thermal evolution characteristic of organic matter of Lower Cretaceous source rock in Erlian Rift system. Xinjiang Petroleum Geology. 1998. 19(6): 476-479 (in Chinese)

Föllmi K B. Early Cretaceous life, climate and anoxia. Cretaceous Research. 2012. 35: 230-257

Friedrich O, Norris R D and Erbacher J. Evolution of middle to Late Cretaceous oceans—A 55 my record of Earth's temperature and carbon cycle. Geology. 2012. 40(2): 107-110

Fu Q, Li Y, Zhang G D, et al. Evidence of the transgression lake of the Subei basin during Late Cretaceous and Paleocene and its geological significance. Frontiers of Earth Science in China. 2008. 2(1): 114-119

Fu X G, Wang J, Zeng Y, et al. Concentrations and modes of occurrence of platinum group elements in the Shengli River oil shale, northern Tibet, China. Fuel. 2010. 89(12): 3623-3629

Gao J W, He D F and Wang Z M. Formation and distribution of giant oil and gas fields in North America petroliferous domain. China Petroleum Exploration. 2011. 3: 44-56 (in Chinese)

Gentzis T, Goodarzi F, Cheung F K, et al. Coalbed methane producibility from the Mannville coals in Alberta, Canada: A comparison of two areas. International Journal of Coal Geology. 2008. 74(3): 237-249

Guardado L R, Spadini A R, Brandao J S L, et al. Petroleum system of the Campos Basin, Brazil. In: Mello M R and Katz B J (eds). Petroleum systems of South Atlantic margins. 2000. AAPG Memoir 73, Chapter 22: 317-324

Hao Y Q, Lin W D, Dong W H, et al. Correlation of hydrocarbon accumulation conditions in Yin' e Basin and Erlian Basin and selection of favorable prospecting zones. Xinjiang Petroleum Geology. 2006. 27(6): 664-666 (in Chinese)

Harris N B, Freeman K H, Pancost R D, et al. The character and origin of lacustrine source rocks in the Lower Cretaceous synrift section, Congo Basin, west Africa. AAPG Bulletin. 2004. 88(8): 1163-1184

He G Q, Zhong J F and Wei W. Characteristics of Lower Cretaceous source rocks in Liupanshan Basin. Journal of Oil and Gas Technology. 2007. 29(3): 23-35 (in Chinese)

He J, He D F, Li S L, et al. Formation and distribution of giant oil and gas fields in Passive Continental Margin of South Atlantic Ocean—A case study of Santos Basin in Brazil. China Petroleum Exploration. 2011. 3: 57-67 (in Chinese)

Hou Z M, Liu M H, Yuan G L, et al. Preliminary evaluation of the source rocks from the Lower Cretaceous coal measure strata in the Shuangyashan Basin, China. Journal of Oil and Gas Technology. 2009. 31(2): 201-204 (in Chinese)

Hou Z M, Xu H J, Hu Z F, et al. Evaluation of the source rocks from the Lower Cretaceous coal measure strata in the Suibin depression of Sanjiang Basin, China. Journal of Chengdu University of Technology (Science & Technology Edition). 2010. 37(1): 15-20 (in Chinese)

Hu G, Hu W X, Cao J, et al. Source rock features and resource potential of the Lower Cretaceous strata in coastal southeast China. Geological Journal of China Universities. 2011a. 17(2): 206-219 (in Chinese)

Hu G, Hu W X, Cao J, et al. The Zircon U-Pb dating of the Lower Cretaceous Bantou Formation in Western Fujian and stratigraphic correlation. Advances in Earth Sciences. 2011b. 26(9): 933-943 (in Chinese)

Hu G, Hu W X, Cao J, et al. Deciphering the Early Cretaceous transgression in coastal southeastern China: Constraints based on petrography, paleontology and geochemistry. Palaeogeography, Palaeoclimatology, Palaeoecology. 2012a. 317: 182–195

Hu G, Hu W X, Cao J, et al. Zircon U-Pb dating of the Shipu limestone in Zhejiang Province, coastal southeast China: Implications for the Early Cretaceous environment. Cretaceous Research. 2012b. 37: 65-75

Hu X M, Wagreich M and Yilmaz I O. Marine rapid environmental/climatic change in the Cretaceous greenhouse world. Cretaceous Research. 2012c. 38: 1-6

Huang Y J, Wang C S and Gu J. Cretaceous Oceanic Anoxic Events: research progress and forthcoming prospects. Acta Geologica Sinica. 2008. 82(1): 21-30 (in Chinese)

Huang Y L, Wang P J, Shu P, et al. Characteristics and formation mechanism of the Cretaceous intermediate and mafic volcanic reservoirs in Songliao Basin, NE China. Acta Petrologica Sinica. 2010. 26(1): 82-92 (in Chinese)

Irving E, North F K and Couillard R. Oil, climate, and tectonics. Canadian Journal of Earth. 1974. 11: 1-17

Jenkyns H C. Geochemistry of oceanic anoxic events. Geochemistry, Geophysics, Geosystems. 2010. 11(3): 1-30

Jenkyns H C, Schouten-Huibers L, Schouten S, et al. Warm Middle Jurassic–Early Cretaceous high-latitude sea-surface temperatures from the Southern Ocean. Climate of the Past. 2012. 8(1): 215-226

Jia J L, Liu Z J, Bechtel A, et al. Tectonic and climate control of oil shale deposition in the Upper Cretaceous Qingshankou Formation (Songliao Basin, NE China). International Journal of Earth Sciences. 2013. 102(6): 1717-1734

Jia X L, He D F, Tong X G, et al. Formation and distribution of giant gas fields in Persian Gulf Basin. China Petroleum Exploration. 2011. 3: 8-23 (in Chinese)

Klemme H D and Ulmishek G F. Effective petroleum source rocks of the world: Stratigraphic distribution and controlling depositional factors. AAPG Bulletin. 1991. 75(12): 1809-1851

Корчагин В И and Shi D. The spatial and temporal distribution of the world's oil and gas fields. Natural Gas Geoscience. 1996. 7(4): 20-28 (in Chinese)

Li J K, Liu W and Song L B. A study of hydrocarbon generation conditions of deep source rocks in Xujiaweizi Fault Depression of the Songliao Basin. Natural Gas Industry. 2006. 26(6): 21-24 (in Chinese)

Li S J, Xiao K H, Wo Y J, et al. Developmental controlling factors of Upper Ordovician–Lower Silurian high quality source rocks in marine sequence, South China. Acta Sedimentologica Sinica. 2008. 26(5): 872-880 (in Chinese)

Li Z D, Li Y, Zhang H X, Chen Z W, et al. Petroleum accumulation conditions of Damoguaihe Formation in Urxun—Beier Sags, Hailaer Basin. Petroleum Geology & Experiment. 2011. 33(5): 480-487, 494 (in Chinese)

Li Z X, He J L, Xiong X G, et al. The Upper Jurassic–Lower Cretaceous Shenglihe oil shales and their formation in the Qiangtang Basin, Northern Xizang. Journal of Jilin University (Earth Science Edition). 2010. 40(2): 264-272 (in Chinese)

Liu B B. Analysis of source–reservoir–cap rock assemblage in Biru Basin. Offshore Oil. 2010. 31(1): 31-35 (in Chinese)

Liu G D, Yang C C and Wang Q C. Physical condition favoring formation of marine hydrocarbon source rocks. Chinese Journal of Geology. 2011. 46(1): 1-4 (in Chinese)

Liu L F and Jin Z J. Distribution of major hydrocarbon source rocks in China's large and medium-sized oil and gas fields. Acta Petrolei Sinica. 2002. 23(5): 6-13, 18-19 (in Chinese)

Lu S F, Chen F W, Li J J, et al. Identification of the lower limit of high-quality source rocks and its relation to hydrocarbon accumulation—Taking the Beier Sag in the Hailaer Basin as an example. Petroleum Science. 2012. 9(1): 10-17

Ma L Y and Cheng K M. Comparison of the hydrocarbon-generating conditions of the Lower Cretaceous from the Jiuxi and Jiudong Depressions. Acta Sedimentologica Sinica. 2012. 30(2): 392-398 (in Chinese)

Meng Y L, Xiao L H, Hou C Y, et al. Geochemical characteristics of Lower Cretaceous source rocks in Gonghe basin of Qinghai and its importance for petroleum generation. Acta Petrologica Sinica. 1999. 15(4): 630-637 (in Chinese)

Moreno-Bedmar J A, Bover-Arnal T, Barragán R, et al. Uppermost Lower Aptian transgressive records in Mexico and Spain: chronostratigraphic implications for the Tethyan sequences. Terra Nova. 2012. 24(4): 333-338

Moriya K. Development of the Cretaceous greenhouse climate and the oceanic thermal structure. Paleontological Research. 2011. 15(2): 77-88

Moshier S O and Waples D W. Quantitative evaluation of Lower Cretaceous Mannville Group as source rock for Alberta's oil sands. AAPG Bulletin. 1985. 69(2): 161-172

Nabikhani N, Moussavi-Harami R, Mahboubi A, et al. The evaluation of reservoir quality of Sarvak Formation in one of oil fields of the Persian Gulf. Journal of Petroleum Science and Technology. 2012. 2(1): 3-15

Nan Z B, Zhang Y L, Li Y T, et al. Comparative analysis of main depositional basin of Qinghai-Tibet Plateau and Tethys Domain. Natural Gas Geoscience. 2012. 23(6): 1039-1044 (in Chinese)

Palacas J G, Anders D E and King J D. South Florida Basin—a prime example of carbonate source rocks of petroleum. In: Palacas J G (Ed), Petroleum geochemistry and source rock potential of carbonate rocks.

AAPG Studies in Geology. 1984. 18: 71-96

Parsons M G, Zagaar A M and Curry J J. Hydrocarbon occurrences in the Sirte Basin, Libya. In: Miall D A (Ed), Facts and Principles of World Petroleum Occurrence: Canadian Society of Petroleum Geologists. 1980. 6: 723-732

Peters K E, Magoon L B, Bird K J, et al. North Slope, Alaska: Source rock distribution, richness, thermal maturity, and petroleum charge. AAPG Bulletin. 2006. 90(2): 261-292

Powell T. Petroleum geochemistry of the Verril Canyon Formation: a source for Scotian Shelf hydrocarbons. Bulletin of Canadian Petroleum Geology. 1982. 30(2): 167-179

Qin Y Q, Hou X L, Deng H W, et al. Hydrocarbon accumulation and exploration potential of East Venezuela Basin. China Petroleum Exploration. 2012. 3: 56-62 (in Chinese)

Qiu C G and Liu Y L. Comparative study of North and South Sub-basins of Gabon Coastal Basin. Geoscience. 2012. 26(1): 154-159 (in Chinese)

Quintero K, Lo Monaco G, Lopez L, et al. Potential petroleum source rocks in a Tertiary sequence of the Eastern Venezuelan Basin. Journal of South American Earth Sciences. 2012. 37: 256-265

Rabbani A R and Kamali M R. Source rock evaluation and petroleum geochemistry, offshore SW Iran. Journal of Petroleum Geology. 2005. 28: 413-428

Rahmani O, Aali J, Mohseni H, et al. Organic geochemistry of Gadvan and Kazhdumi formations (Cretaceous) in South Pars field, Persian Gulf, Iran. Journal of Petroleum Science and Engineering. 2010. 70(1): 57-66

Rangel A, Parra P and Niño C. The La Luna Formation: chemostratigraphy and organic facies in the Middle Magdalena Basin. Organic Geochemistry. 2000. 31: 1267-1284

Ren Y J and Zha M. Organic geochemistry characteristics of Cretaceous source rocks in northeast Jiaolai Basin. Journal of the University of Petroleum, China. 2003. 27(5): 16-20 (in Chinese)

Robison C R. Hydrocarbon source rock variability within the Austin Chalk and Eagle Ford Shale (Upper Cretaceous), East Texas, U.S.A. International Journal of Coal Geology. 1997. 34: 287-305

Sachse V F, Littke R, Jabour H, et al. Late Cretaceous (Late Turonian, Coniacian and Santonian) petroleum source rocks as part of an OAE, Tarfaya Basin, Morocco. Marine and Petroleum Geology. 2012. 29: 35-49

Schaefer R G, Galushkin Y I and Kolloff A, et al. Reaction kinetics of gas generation in selected source rocks of the West Siberian Basin: implications for the mass balance of early-thermogenic methane. Chemical Geology. 1999. 156(1): 41-65

Schieber J. Marcasite in black shales—a mineral proxy for oxygenated bottom waters and intermittent oxidation of carbonaceous muds. Journal of Sedimentary Research. 2011. 81(7): 447-458

Schoellkopf N B and Patterson B A. Petroleum systems of Offshore Cabinda, Angola. In: Mello M R and Katz B J (eds). Petroleum systems of South Atlantic margins. 2000. AAPG Memoir 73, Chapter 25: 361-376

Shu L S, Zhou X M, Deng P, et al. Mesozoic tectonic evolution of the Southeast China Block: New insights from basin analysis. Journal of Asian Earth Sciences. 2009. 34(3): 376-391

Skelton P W. The Cretaceous World. London: Cambridge University Press. 2003. 1-350

Skelton P W, Sano S I and Masse J P. Rudists and the Pacific in the Late Jurassic and Early Cretaceous. Scripta Geologica. 2011. 142: 13-14

Skelton P W, Sano S I and Masse J P. Rudist bivalves and the Pacific in the Late Jurassic and Early Cretaceous. Journal of the Geological Society. 2013. 170(3): 513-526

Spicer R A and Herman A B. The Late Cretaceous environment of the Arctic: A quantitative reassessment based on plant fossils. Palaeogeography, Palaeoclimatology, Palaeoecology. 2010. 295(3): 423-442

Sun Y, Zhong J H, Wang Z K, et al. Organic facies study of Late Cretaceous source rocks in Changling Sag. Journal of Oil and Gas Technology. 2008. 28(4): 171-175 (in Chinese)

Su Y S, Gao J H, Li S J, et al. The basin growth characteristic and hydrocarbon assessment of the Mesozoic in Songnan-Liaoxi Area. Geoscience. 2008. 22(4): 505-511, 519 (in Chinese)

Tao M X. The properties, divisions and oil-gas-forming specialization of the tectonic environment of Chinese oil-gas-bearing areas. Advances in Earth Sciences. 2001. 16(6): 746-754 (in Chinese)

Tian N X, Chen W X, Huo H, et al. Petroleum geologic characteristics and play prediction in the Sirte Basin, Libya. Oil & Gas Geology. 2008. 29(4): 485-490 (in Chinese)

Tu J Q, Chen J P, Zhang D J, et al. A petrographic classification of macerals in lacustrine carbonate source rocks and their organic petrological characteristics: A case study on Jiuxi basin, NW China. Acta Petrologica Sinica. 2012. 28(3): 917-926 (in Chinese)

Wagreich M. "OAE 3"—a low- to mid-latitude Atlantic oceanic event during the Coniacian-Santonian. Climate of the Past Discussions. 2012. 8(2): 1209-1227

Wagreich M, Hu X M and Sageman B. Causes of oxic–anoxic changes in Cretaceous marine environments and their implications for Earth systems—An introduction. Sedimentary Geology. 2011. 235(1): 1-4

Wang C S, Hu X M, Huang Y J, et al. Cretaceous oceanic red beds as possible consequence of oceanic anoxic events. Sedimentary Geology. 2011. 235(1): 27-37

Wang L C, Wang C S, Wu X H, et al. Evaluation of Jurassic-Cretaceous marine hydrocarbon rocks in the Bolin Basin, Southwestern Tibet. Petroleum Geology & Experiment. 2010. 32(3): 276-281 (in Chinese)

Wang X M, Guo Y R, Ma L, et al. Yin'e Basin: Characters of Jurassic and Cretaceous petroleum supersystem and prospecting area. Advances in Earth Sciences. 2001. 16(4): 490-495 (in Chinese)

Wang X M, Zheng H R, Wang Y, et al. Characteristics of the Lower Cretaceous source rock in Biru Basin, Tibet. Acta Petrolei Sinica. 2012a. 33(5): 822-829 (in Chinese)

Wang X Y, Hu W X, Hu G, et al. Microfacies and zircon U-Pb dating of the Lower Cretaceous Shipu Limestone in Xiangshan, Eastern Zhejiang. Geological Review. 2012b. 58(4): 614-626 (in Chinese)

Wei D T, Jia D, Zhao Y C, et al. The formation of Cretaceous source derived oils in the Southern Junggar Basin, NW China. Geological Review. 2008. 54(3): 399-408 (in Chinese)

Wei Y S, Wang C S, Li Y L, et al. Characteristics of Mesozoic source–reservoir–cap rock association and hydrocarbon prospect evaluation in the Cuoqin basin, Tibet. Geological Bulletin of China. 2011. 30(10): 1575-1586 (in Chinese)

Wu H C, Zhang S H and Huang Q H. Establishment of floating astronomical time scale for the terrestrial Late Cretaceous Qingshankou Formation in the Songliao Basin of northeast China. Earth Science Frontiers. 2008. 15(4): 159-169

Wu S B and Bai Y B. Jurassic-Cretaceous source rock–reservoir–cap associations and hydrocarbon potentials in the Beishan Basins. Chinese Journal of Geology (Scientia Geologica Sinica). 2006. 41(1): 1-9 (in Chinese)

Xia K Y, Huang C L and Huang Z M. Upper Triassic–Cretaceous sediment distribution and hydrocarbon potential in South China Sea and its adjacent areas. China Offshore Oil. 2004. 16(2): 73-83 (in Chinese)

Xie X M, Hu W X, Cao J, et al. Preliminary investigation on depositional environment of black mud in Lower Cretaceous, Zhejiang and Fujian provinces: micropaleontology and organic geochemical evidences. Acta Sedimentologica Sinica. 2010. 28(6): 1108-1116 (in Chinese)

Xu D J, Zhang W C, Du X J, et al. Reservoir characteristics and development suggestions of chalky limestone in the Zagros Basin, Iran. Petroleum Geology & Experiment. 2010. 32(1): 15-18, 23 (in Chinese)

Xu Y C, Wang Z Y, Wang X F, et al. Low-mature gases and typical low-mature gas fields in China. Science in China Series D: Earth Sciences. 2008. 51(2): 312-320

Yao Y J, Li X J, Yang C P, et al. Tectonic characteristic and hydrocarbon resource potential in the North Slope Basin of Alaska, the Arctic. Marine Geology Frontiers. 2011. 27(12): 18-26 (in Chinese)

Yu M D, Wang P J, Jiang Y F, et al. Geochemical characteristics of source rocks and its hydrocarbon generation potential in the Dunhua Basin. Petroleum Geology & Experiment. 2008. 30(3): 270-275 (in Chinese)

Yu Y X, Tang L J, Yin J Y, et al. Tectonic and hydrocarbon accumulation elements characteristics of the Tethyan realm in South China. Acta Geologica Sinica (English Edition). 2009. 83(6): 1214-1223

Zhai S D, Ren Y J and Zha M. Biomarkers from Cretaceous source rocks in Jiaolai Basin. Xinjiang Petroleum Geology. 2003. 24(5): 392-395 (in Chinese)

Zhang K. Strategic replacement situation and outlook of China oil-gas production area. Petroleum Exploration and Development. 2012. 39(5): 513-523 (in Chinese)

Zhang Z, Li H W, Duan H Z, et al. Geological characteristics and hydrocarbon accumulation model of the Cenozoic Asmari-Gachsran play, Zagros Basin. Oil & Gas Geology. 2012. 33(2): 190-199 (in Chinese)

Zhao Q F, Gong J M, Li S L, et al. Pre-Tertiary deepwater oil plays in the Northern Gulf of Mexico Basin. Marine Geology Frontiers. 2011. 27(4): 11-14 (in Chinese)

Zhou S Y. Characteristics of Cretaceous petroleum system in Yiyang Basin, Jiangxi Province. Xinjiang Petroleum Geology. 2000. 21(2): 116-119 (in Chinese)

Zou C N, Zhu R K, Zhao W Z, et al. Geologic characteristics of volcanic hydrocarbon reservoirs and exploration directions in China. Acta Geologica Sinica (English Edition). 2010. 84(1): 194-205

**(Edited by Hao Jie)**