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River-gulf system—the major location of marine source rock formation

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Abstract: Petroleum was generated from sedimentary rocks. The world's oldest oil source rock so far was found in Proterozoic rocks. Since then, 73% to 81% of the earth's surface has been covered with sedimentary rocks. However, only quite a limited area is rich in oil and gas. It is found that source rocks have controlled oil and gas distribution, and they are mainly formed in two systems: (1) river-lake systems and (2) river-gulf systems. Phytoplankton is an important source of kerogen, the blooming of which is strongly dependent on nutrients. Rivers are the major nutrient provider for basins. Rivers around lakes and an undercompensation (where the sedimentation rate is less than the rate of basin subsidence) environment provide favorable conditions for phytoplankton blooming in lakes. Gulfs are usually located at the estuary of big rivers, characterized by restricted current circulation and exchange with the open sea, which benefit maintaining the nutrient density, phytoplankton levels and organic matter preservation. The river-gulf system is the most favorable place for marine source rock development. Most of the world famous marine petroleum-rich provinces are developed from river-gulf systems in geological history, such as the Persian Gulf Basin, Siberian Basin, Caspian Basin, North Sea, Sirte Basin, Nigerian Basin, Kwanza Basin, Gulf of Mexico, Maracaibo Basin and the Eastern Venezuelan Basin.

Key words: Nutrient supply, river-gulf system, marine source rock, oil-bearing basin

1 Conditions for the development of marine source rocks

Petroleum was generated from organic matter in sedimentary rocks under high temperature (60-250°C), and marine petroleum originated from marine source rocks. Drilling data has revealed that the oldest source rock yet found in the world is the Neo-Proterozoic Riphean source rock in the East Siberian Basin (Li and Jin, 2005). Most of the earth surface has been covered by sea at some time (accounting for 73%-81%) and many marine basins developed (Wang and Liu, 1980). However, long-term exploration activities have revealed that petroleum–bearing basins, especially commercial oilfields–bearing basins, only account for a small proportion and cover a very small area. There are totally 624 large and middle-scale basins in the world, only 160 of which are hydrocarbon-rich (Zou et al, 2010). There are so many marine sedimentary basins in the world. Which basins with high quality source rocks and large hydrocarbon resources deserve our special attention? Which basins have poor source rocks and little hydrocarbon prospect? These are the most important and urgent issues for us to answer. The author has been thinking about the issues for seven years. Based on the analysis of the global exploration data, it is concluded that the river-gulf system is the major location of marine source rock formation.

Rivers carry clastics to the continental margin and form fluvial-delta systems. It is well-known that fluvial-delta sandstones are major reservoirs. However, a greater contribution of rivers to petroleum includes source rocks as well as reservoirs. Rivers transfer and provide nutrients for organism growth. It is well known that petroleum was generated by organic matter in sedimentary rocks and the richness of organic matter determined the amount of hydrocarbon generated. Organic matter mainly originates from phytoplankton whose living environment requires high temperature, clean water, appropriate salinity and rich nutrient levels. Further research indicated that water temperature, cleanness and salinity are similar in close latitudes, but nutrient richness differs a lot. Thus it can be concluded that the nutrient richness determines the abundance of phytoplankton. Red tides and blue tides are typical examples, which are quite common today in China's Bohai and the South China Sea. The reason for frequent red tides and blue tides is the abundant nutrients in the sewage draining to the sea, which caused the blooming of algae. Algae are an important origin of kerogen. It could be deduced that the abundance of ancient phytoplankton depends on nutrient richness.

Organic matter is the origin of petroleum. Global exploration has revealed that back-arc basins are rich in

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petroleum resources, whereas fore-arc basins are poor (Tong, 2002). This is because back-arc basins have a large river inflow which provides nutrients for phytoplankton growth, whereas, fore-arc basins have no rivers feeding them. That is why petroleum-rich basins are common on the continental margins with river influx. Rivers brought abundant fossil fragments which later formed kerogen, and meanwhile rivers brought sands and shales building up delta plains in the estuary. The fertile soil of delta plains provided favorable conditions for terrestrial plants to grow and these later became coal and carbonaceous mudstone after they died. Coal and carbonaceous mudstone are major kerogen sources for natural gas. River water contains abundant minerals and organic matter, but rain water has very few nutrients. Submarine volcanoes and oceanic upwelling can also bear nutrients, but these only exist in a few marine basins with specific geological conditions (Tong, 2002). Therefore, rivers are the most important suppliers of nutrient to marine basins. The following cases illustrate that most of the global petroleum-rich marine basins have large river influx and the same is the case for lacustrine basins with more river influx.

A gulf is another major factor controlling the distribution of marine source rocks and hydrocarbons. Gulfs usually have big river influx and in the estuaries big rivers seldom flow into the sea at the convex bank. Gulfs commonly connect with the open sea by narrow channels, two or three sides of which are land. Water circulation and exchange between gulfs and the open sea is restricted, which inhibits the dilution of nutrients and thus ensures nutrients for phytoplankton. On the other hand, the calmness in gulfs ensures phytoplankton is easily preserved on the sea floor after they die. The following examples illustrate that most of the marine petroleum, no matter Paleozoic, Mesozoic or Cenozoic, occurs in present or ancient gulf areas.

2 Geological characteristics of major river-gulf system oil provinces

2.1 Asian gulf basins

Asia is the most important oil production area in the world. The Persian Basin and West Siberian Basin are world famous oil-production basins, and both developed from Mesozoic river-gulf systems and marine source rocks. South, Southwest and Northwest of China also developed gulf systems and marine source rocks. Cenozoic marine deposits are well developed in the southeast coast of China, which mainly produce coaliferous gas. The source rocks were developed in river–open sea system.

2.1.1 China's marine basins

Liang Digang, a famous Chinese geologist, has carried out detailed research into the controlling factors of marine source rocks in the South, Southwest and Northwest of China. He proposed that the gulf systems of different periods (Fig. 1), which were formed by the ancient Qinling Sea, South China Sea and Babu Sea protruding into the Yangtze Craton, are the seedbed of marine source rocks. These areas could be the important fields for South China's marine petroleum exploration (Liang et al, 2009).

China's Cenozoic marine sedimentary rocks are mainly

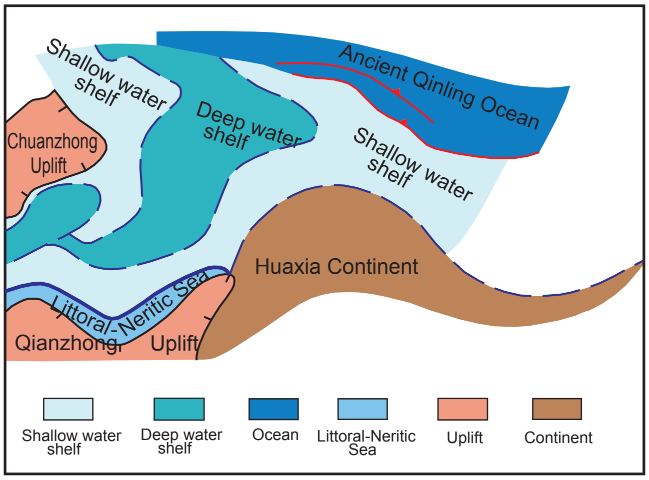

Fig. 1 Silurian depositional environment map of South China by Liang et al (2009)

distributed in the southeast coasts, including the East China Sea Basin, Southwest Taiwan Basin, Zhujiangkou Basin, Southeast Hainan Basin and Yinggehai Basin. Source rocks in these basins are mainly transitional facies coals and carbonaceous mudstones, producing mainly natural gas (Fu et al, 2007; Dong and Huang, 2000). Forty years of exploration indicate that large and middle scale oil and gas fields are all located in the fluvial-delta systems. Liwan 3-1 and Liuhua 30-1 gas fields are located in the ancient Zhujiang fluvial-delta system, Zhuer Depression. Yacheng 13-1 gas field is located in the Yacheng fluvial-delta system, Southeastern Hainan Basin. Dongfang 1-1, Ledong 15-1 and Ledong 22-1 gas fields are located in the ancient Honghe fluvial-delta system, Yinggehai Basin (Deng, 2009). Terrigenous plant fragments carried down by ancient rivers are direct gas kerogen sources for these basins. Furthermore, rivers carried sands and shales building up delta plains on the estuary. Fertile soils of delta plain supported the growth of higher plants and development of coals and carbonaceous mudstones. A river–delta open sea system probably is the most favorable place for coaliferous gas source rocks.

2.1.2 Persian Basin

The Persian Basin is the richest petroliferous basin of the world. The discovered reserves reach about 1,200 BBOE and undiscovered hydrocarbon resources are predicted to be about 355 BBOE. Besides favorable geological conditions such as large scale compression, drape, thrust anticlines, excellent carbonate and sandstone reservoirs, thick mudstone and salt seals, the most important reason for Persian Basin's enrichment is its high quality source rocks. The "Source Rock Control Theory" is fit for every basin. The Persian Basin develops two major source rock intervals. One is Silurian-Devonian "hot shales", which is similar to those in North Africa and formed in Paleo-Tethys margin. These source rocks mainly generated gas due to their high burial depth and high maturity (Zou et al, 2010). A number of giant gas fields, such as the South Pars and North Pars fields, originated from Silurian hot shales. The other is Jurassic-Cretaceous source rocks which developed in a fluvial-gulf system and mainly generated oil.

The Persian Basin is a huge sedimentary basin of 3.5

million km^2 area in Jurassic-Cretaceous. The structure is simple with a slope between the Arab Platform and the basin center. The whole basin has a uniform depositional center and subsidence center (Alsharhan and Kendall, 1986). The basin is surrounded by land except the narrow channel connected with the ocean in the southeast, and it appears a lagoon. In the Jurassic, rivers occurred in the southwest and formed fluvial-delta systems in the southwestern gulf (Fig. 2). In the Cretaceous, rivers flowed into the gulf basin at present Kuwait along the major axis direction of northwest, and built up large scale deltas. It is the ancient Jurassic and Cretaceous big rivers that brought abundant nutrients, meanwhile the semi-closed gulf ensured the nutrient density and the blooming of phytoplankton which supplied the material basis for high quality source rocks. Drilling reveals that Jurassic-Cretaceous source rocks are of type I and II$_1$ kerogen and have high TOC (average 2.6%-3.5%) in the Persian Basin.

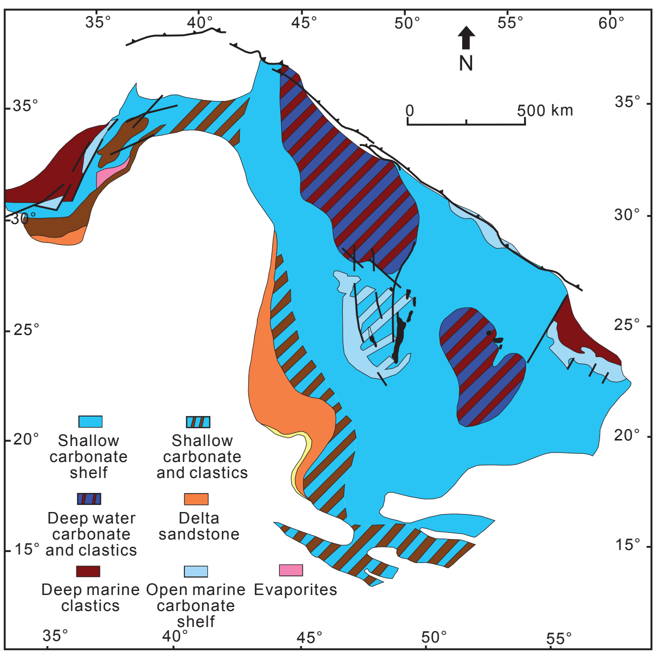

Fig. 2 Late Mid-Jurassic sedimentary facies map of the Persian Basin. Modified after Konert et al (2001)

2.1.3 West Siberian Basin

The West Siberian Basin is the second largest petroliferous basin in the world. Its area reaches 3.3 million km^2. The predicted recoverable reserves are 136 BBO oil and 2470 TCF gas. The petroleum geological conditions are similar to those of the Persian Basin. These are a big area, few faults, simple structures, uniform depositional and subsidence center. The West Siberian Basin has huge drape and compression traps, excellent reservoirs and seals. The major producing reservoir is Cretaceous in age and the major source rock is Jurassic-Cretaceous in age (Jin and Wang, 2007).

The West Siberian Basin was a gulf in the Jurassic and Cretaceous, formed by ocean protruding into the shield. The north-south striking gulf was surrounded by land to the east, south and west, and connected with the ocean only to the north (Jin and Wang, 2007) (Fig. 3). There was an island in the junction area between the ocean and gulf basin. The east and south of the basin were fed by large rivers (Pinous et al, 2001) (Fig. 4) which brought organic matter and minerals to the gulf basin and supplied nutrients for phytoplankton growth. The Jurassic-Cretaceous source rocks contain oil prone sapropel kerogen and the TOC ranges from 2.5% to 7%.

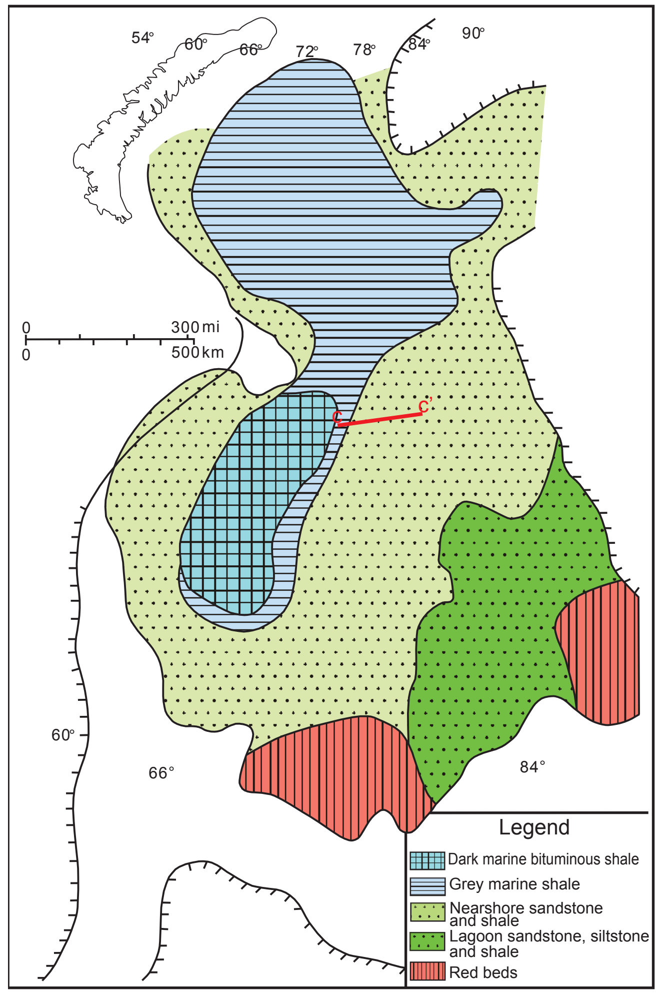

Fig. 3 Upper-Jurassic lithofacies map of the West Siberian Basin

2.2 European gulf basins

The North Sea and the Caspian Sea are important oil producing areas of Europe. The North Sea oil and gas originate from the North Sea Basin. The Caspian Sea oil and gas mainly come from the Pre-Caspian Basin and South Caspian Basin. The Central Caspian Basin is oil-poor. The source rocks of North Sea Basin, Pre-Caspian Basin and South Caspian Basin are marine sedimentary rocks, formed in ancient gulfs.

2.2.1 North Sea Basin

The North Sea Basin is a Mesozoic rift with an area of 575,000 km^2. The proved oil reserves are 110 BBOE and undiscovered resources are estimated to be 22 BBOE. The major reservoirs are Upper Cretaceous to Paleogene in age. The overlying Cretaceous marine shales are the regional seal and the traps are mainly structural traps (Li and Jin, 2005).

The major source rock of North Sea Basin is Jurassic marine shales. The basin was bounded by the Baltic Shield

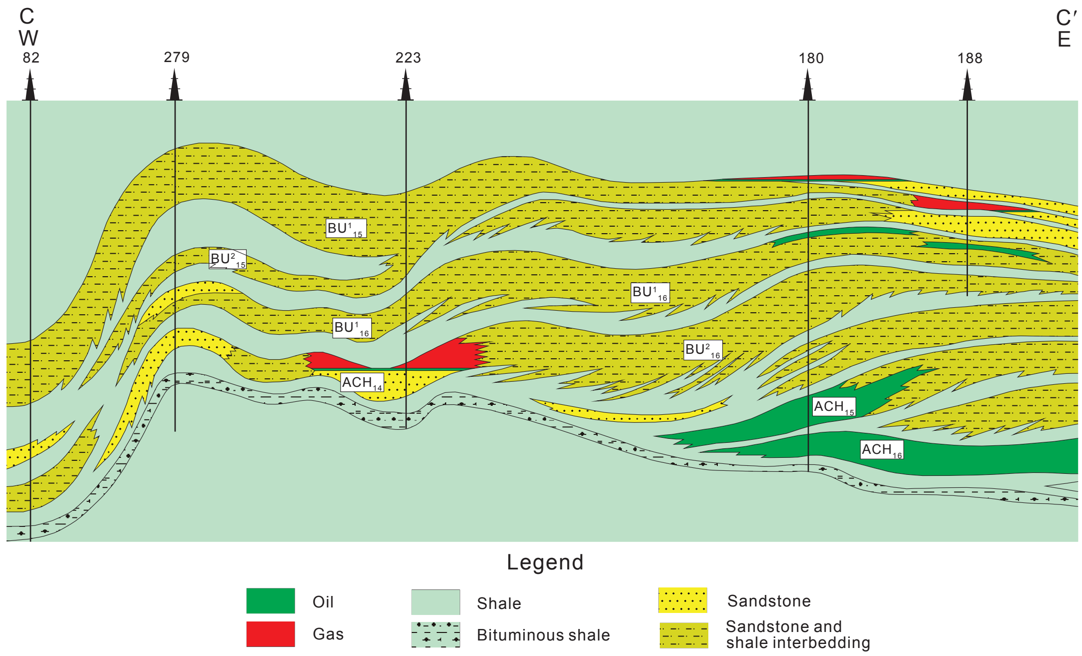

Fig. 4 Jurassic deltaic depositional profile of the West Siberian Basin

to the east, the France-Germany continent to the south and the Laurentian Shield to the west in the Jurassic. Only the north was connected to the ocean and this developed a gulf environment. In the Jurassic, rivers from the southern continent flowed into the basin (Fig. 5). The river brought abundant minerals and organic matter, and kept accumulating phytoplankton which formed the kerogen of the Jurassic source rocks. The Viking Graben has the best source rocks and is the richest structural unit in hydrocarbon resources of the North Sea Basin. The Jurassic source rock is type I and II_1 kerogen (Isaksen and Ledje, 2001), which is mainly contributed by phytoplankton. TOC ranges from 3.1% to 9.0%.

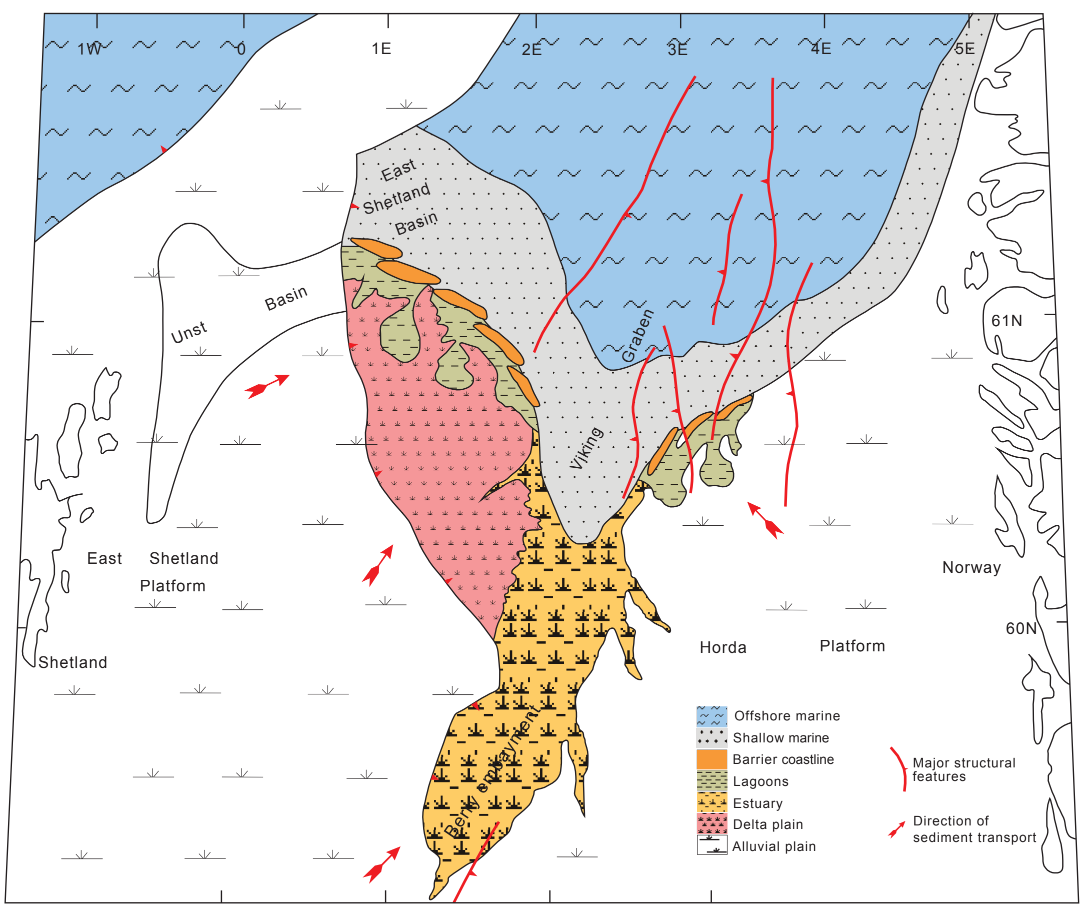

Fig. 5 Jurassic depositional system map of the North Sea Basin

2.2.2 Pre-Caspian Basin

The Pre-Caspian Basin is a large basin of about 500,000 km^2, the proved reserves are 70 BBOE, and undiscovered hydrocarbon resources are supposed to be 49 BBOE. The basin is round in shape, and reefs and carbonate shoals on the marginal uplifts are major oil reservoirs. The thick Permian evaporites are regional seals. The oil and gas fields of large-middle scale are all discovered under the regional evaporate seals. Reefs are major traps (Li and Jin, 2005). The most important source rock is Devonian-Carboniferous marine mudstones, limestone and marls. The basin was a gulf connected with Paleo-Tethys Ocean by a channel to the south and bounded by ancient land to the east, north and west during Devonian-Carboniferous time. Because of the thick deposition (12 km) and thick salt shielding, the seismic data quality in deep layers is poor. Meanwhile, deep wells are rare. All of these have constrained research into Devonian-Carboniferous sedimentary facies and provenance. But it is clear that Pre-Caspian was a gulf basin in geological history.

2.2.3 South Caspian Basin

The South Caspian Basin is a Cenozoic basin with an area of 287,000 km^2. The proved oil reserves are 41 BBOE, and undiscovered hydrocarbon resources are 55 BBOE. This basin is characterized by rapid subsidence and deposition, which led to thick Cenozoic sedimentary rocks (15 km), under-compaction, high formation pressure, high formation temperature and development of mud diapirs and mud volcanoes (Stewart and Davies, 2006). Diapir structures are the main traps, river-delta sandstones are the major reservoirs, and Oligocene-Miocene marine shales are the main source rocks.

The South Caspian Basin developed as a typical river-gulf system. It was a remnant sea, like a big lake in the Cenozoic and there were many rivers flowing into Caspian Sea. The most important one was the ancient Volga River from the northwest, which built up a large delta in the northwestern South Caspian (Zou et al, 2010) (Fig. 6, Fig. 7). Delta sandstones are the major reservoirs. Meanwhile, rivers brought organic matter and minerals which supplied nutrient for phytoplankton growth and terrigenous plant fragments which became kerogen. The TOC of Oligocene-Miocene source rocks ranges from 0.5% to 2% mainly of mixed type.

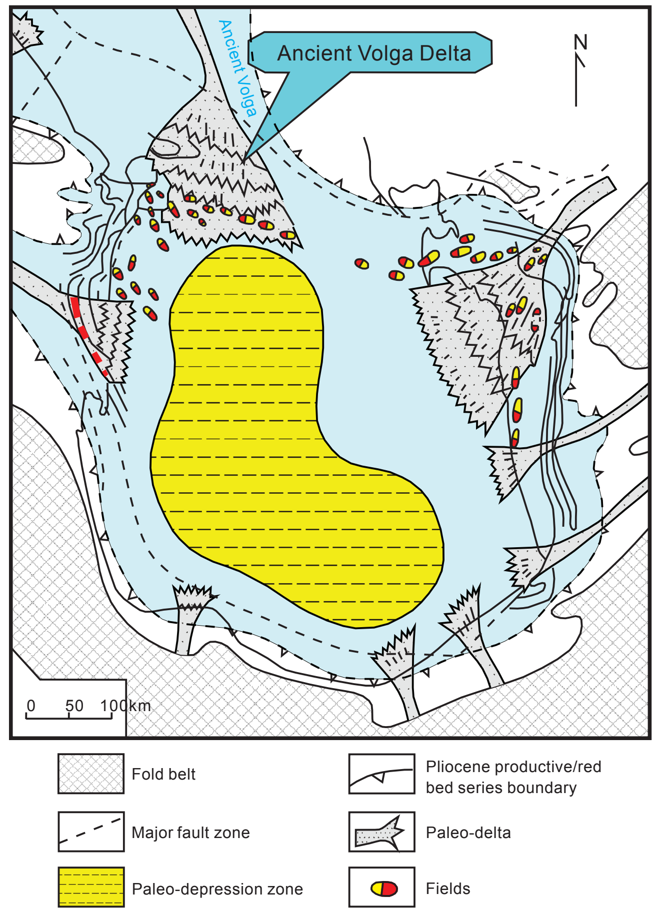

Fig. 6 Pliocene depositional system map of the South Caspian Basin. Modified after Torres (2007)

2.3 African gulf basins

Africa has abundant oil and gas resources. Petroliferous basins are widespread in East Africa, West Africa, North Africa and Interior Africa, in which the West Africa Atlantic margin and North Africa are the most famous oil provinces and the major oil producing area of Africa. East Africa has limited exploration activities and the petroleum geology needs further research. Interior Africa develops two kinds of basins, Paleozoic basins and Mesozoic basins. The former are relatively lightly explored and the geological conditions and exploration potentials are not clear. Most of the Mesozoic interior basins are intra-continental rift basins with lacustrine deposition, such as the Muglad and Melut basins of Sudan and Borgen Basin of Chad. The characteristics of these basins are similar to those in Bohai Bay Basin and Songliao Basin of China. This paper takes the West Africa and North Africa's Mesozoic and Cenozoic basins as examples to demonstrate the control of river-gulf system over the hydrocarbon distribution.

2.3.1 West Africa Atlantic margin basins

The West Africa Atlantic margin is the most important oil producing area in Africa, and the oil distribution along the West Africa Atlantic margin is quite uneven. The formation of Atlantic Ocean and the breakup between Africa and South America plates commenced from the north, and then in the south and finally the middle part (Nigeria). A large amount of drilling data demonstrated that the hydrocarbon distribution along West Africa Atlantic margin is rich in the middle and poor in the north and south, the main reason for which is different source rock conditions. The middle Atlantic margin (Cote D'Ivoire, Nigeria, Equatorial Guinea, Gabon and Angola) has two source rocks. One is Upper Jurassic–Lower Cretaceous lacustrine source rock of rift stage. The other is Mid-Upper Cretaceous–Tertiary passive continental margin marine source rock (Zou et al, 2010). The development conditions for lacustrine source rocks are similar to those in Muglad and Melut basins. Numerous rivers developed around the lakes in both cases, which brought abundant nutrients and maintained the lacustrine phytoplankton growth. Meanwhile, the undercompensation environment favored the development of type I-II$_1$ kerogen source rocks. During the passive continental margin stage of the Mid-Late Cretaceous,

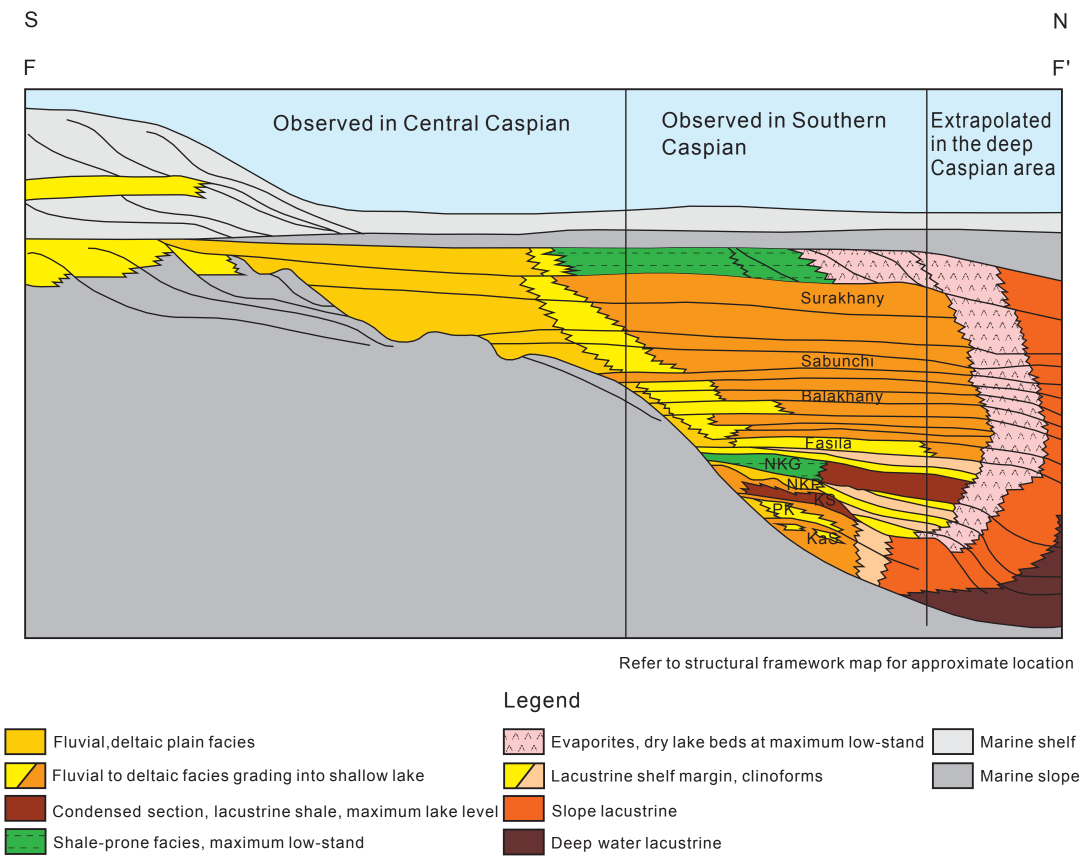

Fig. 7 S-N regional stratigraphic section crossing the ancient Volga River delta of the South Caspian Basin

the Atlantic Ocean commenced to break up and formed an "S"-shaped gulf connected with the open sea to the north and bounded by land to the east, west and south. The African continent was to the east with the South American continent to the west and the Walvis Ridge to the south (Fig. 8). The big rivers such as the Niger and Congo originated from the South African continent and flowed into the calm gulf. They brought clastics and formed deltas (Fig. 9) and submarine fan reservoirs. Meanwhile the minerals and organic matter transported by rivers kept the phytoplankton flourishing and ensured the development of the Middle Cretaceous–Tertiary source rocks. It is clear that lakes, gulfs and associated rivers provide material foundations for the development of oil and gas fields along the middle Africa Atlantic margin.

The Northwest African Atlantic margin has poor source rocks. It did not develop Jurassic–Lower Cretaceous lacustrine source rocks, and no big rivers occurred in Northwest Africa to supply nutrient for phytoplankton growth in Middle Jurassic–Tertiary time. Furthermore, deltas and submarine fans did not develop, which led to a lack of reservoirs. In the Mid Cretaceous–Early Tertiary, only the middle section of West Africa Atlantic margin (Cote D'Ivoire, Benin, Niger Delta, Rio Muni, Gabon and Kwanza basin) was a gulf, which developed a good river-gulf system, excellent source rocks and rich hydrocarbons. The south and north was the open sea, which developed poor source rocks and little hydrocarbon.

2.3.2 Sirte Basin

The Sirte Basin is an important petroliferous basin in North Africa. The area reaches 502,000 km^2. The proved reserves reach 55 BBOE, which account for 96% of Libya. The undiscovered resources are predicted to be 11 BBOE. The Sirte Basin is a Mesozoic intra-cratonic rift basin, and the main rift period is Late-Cretaceous (Abadi et al, 2008). At that time, the Sirte Basin was a typical gulf, connected with the open sea to the north and bounded by land to the east, west and south. Rivers originating from continent brought abundant nutrients, keeping the phytoplankton flourishing. The Upper Cretaceous Sirte shales are the most important source rocks with type I-II$_1$ kerogen. The TOC averages 5%. The Paleocene marine mudstones also have the ability to generate hydrocarbon, but only part of them is mature.

The Sirte Basin develops Lower Cretaceous to Oligocene reservoirs, in which the Lower Cretaceous continental sandstones and Paleocene shallow marine carbonates are the major reservoirs. The well-developed Upper Cretaceous to Oligocene marine mudstones, shales and evaporites form excellent regional seals. Grabens, tilted fault blocks associated with normal faulting activities and drape anticlines on basement uplifts are the main oil traps.

2.4 American gulf basins

The Americas are rich in oil and gas resources. Alberta, Los Angeles, Gulf of Mexico, Maracaibo, Eastern Venezuelan

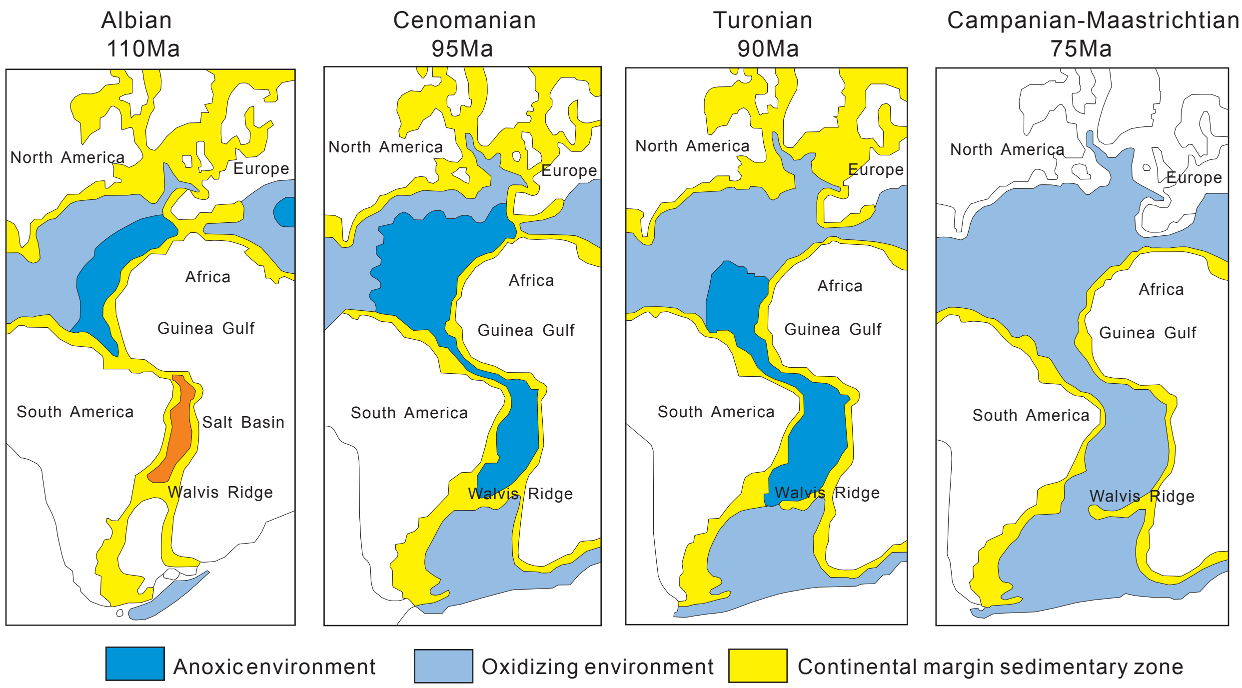

Fig. 8 Evolution of the West Africa Atlantic margin basins by previous authors showing the anoxic environment during the Mid-Cretaceous between the Walvis Ridge and Middle Atlantic ocean

and Campos-Santos Basins are all world famous oil producing areas. The source rocks in these basins have two development environments: (1) lake and (2) gulf. The Campos Basin and Santos Basin are mainly Cretaceous lacustrine mudstone source rocks, which is similar to China's Songliao Basin and Bohai Bay Basin. The lakes were small, and under an undercompensation environment rivers brought abundant nutrient which kept algae flourishing and later formed the excellent kerogen. Other basins develop gulf source rocks, and the Gulf of Mexico, Maracaibo and Eastern Venezuelan basins are to be discussed as examples in the following.

2.4.1 Gulf of Mexico Basin

The Gulf of Mexico Basin is the third largest petroleum-rich basin in the world. It has an area of 1.3 million km^2 and is a Mesozoic-Cenozoic marginal rift basin. The basin developed several intervals of marine shale source rocks from Upper Jurassic to Pleistocene (Li and Jin, 2005). The TOC reaches 1%-16% and is of type I-II kerogen. During the long evolution from Mesozoic to Cenozoic, the Gulf of Mexico was always a semi-closed gulf (Galloway et al, 2000) (Fig. 10), the north of which was land, the east, south and west of which was peninsula and islands chain. Extensive distribution of salt and anhydrite proves the gulf was closed at some stages. The western Texas River and eastern Mississippi River (Fig. 11) carried enough nutrients to support the growth of algae which formed kerogen.

The main reservoirs of the Gulf of Mexico are delta sandstones, beach sandstones, shelf carbonates and reefs. Thick evaporites and marine mudstones are excellent regional seals. Salt-related diapirs and piercing structures, rollover

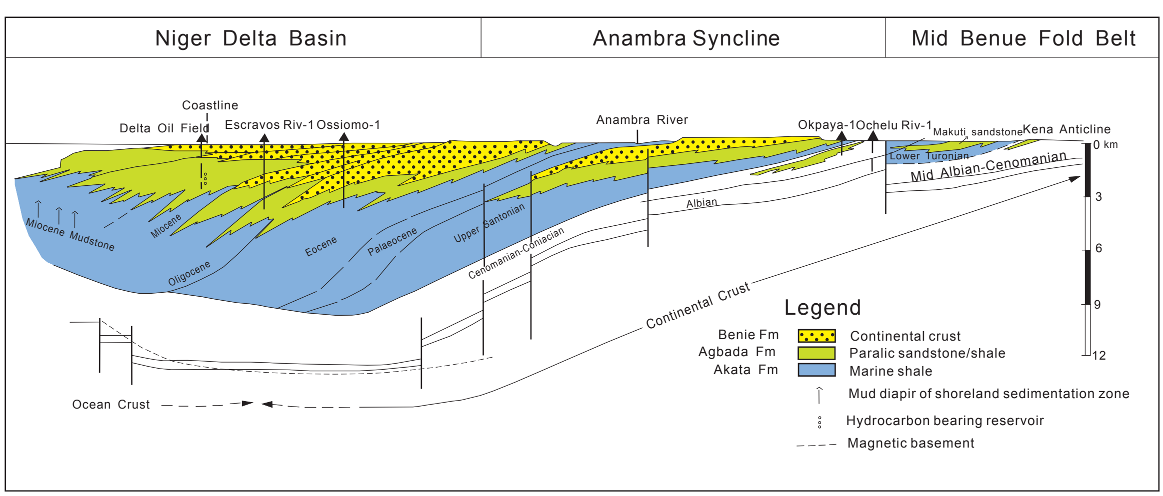

Fig. 9 Geological section of the Niger Delta. Modified after Saugy et al (1977)

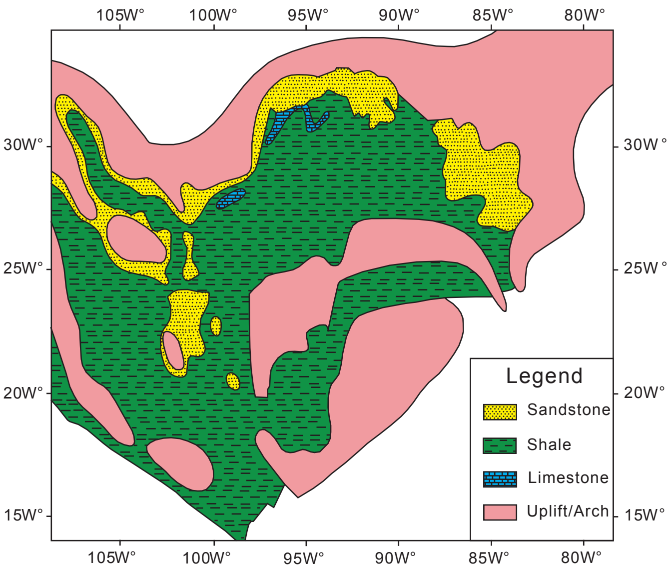

Fig. 10 Late Jurassic depositional system map of the Gulf of Mexico Basin. Modified after Jacques and Clegg (2002)

structures, fault noses and fault blocks are major oil traps.

2.4.2 Maracaibo Basin

Maracaibo is an important oil producing basin of South America. It has an area of 80,000 km^2, 76 BBOE proved reserves and an estimated 12 BBOE undiscovered resources. It is a superimposed basin, which was a continental rift basin filled with coarse lacustrine deposits in the Jurassic, and passive margin marine basin with marine shale and mudstone source rocks in the Cretaceous-Paleogene (Mann et al, 2006). Finally, the basin reversed to a foreland basin which was filled with delta deposits after the Eocene (Li and Jin, 2005).

The sedimentary environment of the Maracaibo Basin is partly inherited from the Cretaceous till now. At present, the basin has shrunk to a lagoon. The basin was a gulf in the Cretaceous, connected with the open sea to the north and bounded by land to the east, south and west. Rivers from the south transported clastics and formed the delta sandstone reservoirs. Moreover, mineral and organic matter in rivers supplied nutrients for phytoplankton which later became kerogen. The Cretaceous source rocks are type I-II kerogen with 10% TOC. The Eocene delta sandstones are the main reservoirs with good properties. Compression-thrust anticlines are major oil traps.

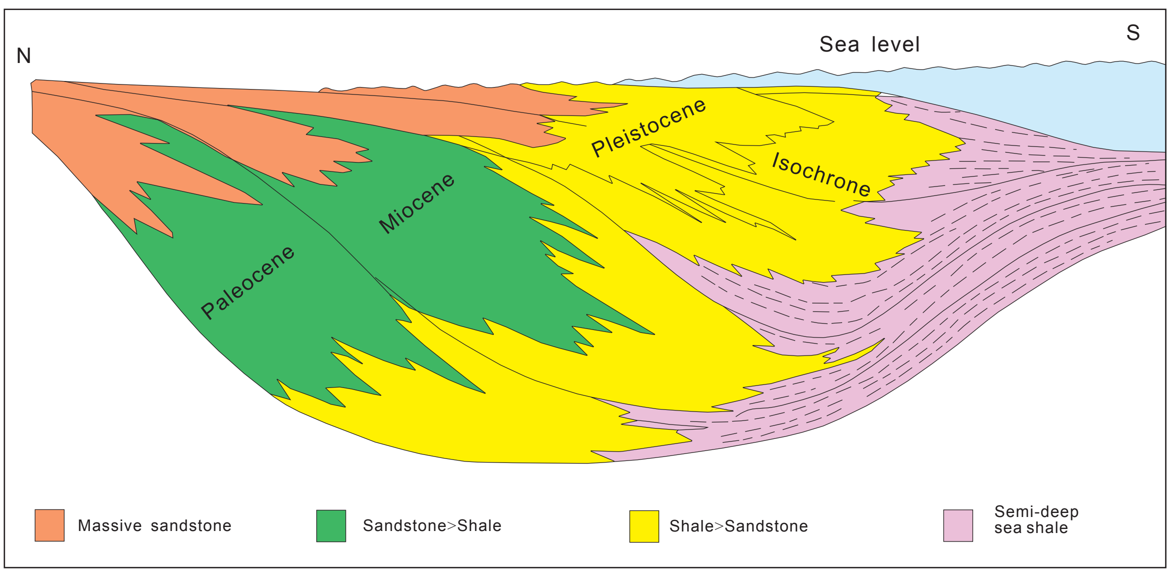

Fig. 11 Paleotectonics and sedimentary section of the Gulf of Mexico Basin

2.4.3 Eastern Venezuelan Basin

The Eastern Venezuelan Basin is one of the richest petroliferous basins in South America. The Orinoco heavy oil belt in the south alone has reached 1400 BBOE OOIP, which is the largest heavy oil belt in the world. The area of this basin is 200,000 km^2. This basin is similar to the Maracaibo Basin nearby in basin type and evolution. The major source rocks were formed during the Cretaceous passive margin stage. At that time, the basin was a nearly east-west narrow gulf. The south, west and north sides were land. Only the east and north-east had two channels connected with the open sea. The big rivers originating from the broad southern continent flowed into the gulf and carried nutrients. Furthermore, the basin was relatively closed. The water exchange was restricted, which kept high levels of nutrients and supported phytoplankton flourishing. The Cretaceous limestones and shales are main source rocks with type I-II kerogen, and TOC ranges from 0.5% to 6.6%. Delta sandstones are excellent reservoirs. The Orinoco heavy oil belt is on the delta. Because of the poor trap type (unconformity trap), light components evaporated and the heavy oils were left.

3 Conclusions

1) The distribution of oil and gas is quite uneven in the world. 73%-81% of earth surface has been sedimentary basins since the Proterozoic. However, oil and gas only exist in quite limited area. Data indicates that 75% of the large-middle-scale basins in the world are oil poor.

2) Petroleum was generated by organic matter which mainly originated from phytoplankton. The living environment of phytoplankton requires high temperature, clean water, appropriate salinity and rich nutrient. It is found that water temperature, cleanness and salinity are similar in close latitudes, but nutrient levels differ a lot. Thus, the abundance of phytoplankton is mainly determined by nutrient levels.

3) Submarine volcanoes and oceanic upwelling which can also supply nutrient for phytoplankton growth occur only in few specific basins. For most of the sedimentary basins in the world, nutrient for phytoplankton growth is provided by rivers.

4) Gulfs which commonly have substantial river influx are characterized by calm and semi-closed environment with weak waves and current circulation, restricted and slow material exchange. All of above make the gulf a favorable place for high nutrient levels, blooming of phytoplankton and preservation of organic matter. That is why the world's marine oil is mainly distributed in the river-gulf systems.

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