Available online at www.sciencedirect.com

ScienceDirect

Natural Gas Industry B 2 (2015) 49–76

www.elsevier.com/locate/ngib

Research article

Analysis of the orderly distribution of oil and gas fields in China based on the theory of co-control of source and heat

Zhang Gongcheng, Jin Li, Lan Lei*, Zhao Zhao

CNOOC Research Institute, Beijing 100027, China

Available online 29 May 2015

Abstract

Taking a hydrocarbon zone or a basin group as a unit, this paper analyzed the vertical hydrocarbon generation regularity of onshore and offshore oil and gas fields in China, based on the theory of co-control of source and heat. The results demonstrated that the hydrocarbon generation modes of oil and gas fields in China are orderly. First, the hydrocarbon zones in southeastern China offshore area, including the East and South China Sea basins, are dominated by single hydrocarbon generation mode, which displays as either single oil generation in the near shore or single gas generation in the offshore controlled by both source and heat. Second, the eastern hydrocarbon zones, including the Bohai Bay, Songliao and Jianghan basins and the North and South Yellow Sea basins, are dominated by a two-layer hydrocarbon generation mode, which performs as "upper oil and lower gas". Third, the central hydrocarbon zones, including the Ordos, Sichuan and Chuxiong basins, are also dominated by the "upper oil and lower gas" two-layer hydrocarbon generation mode. In the Ordos Basin, gas is mainly generated in the Triassic, and oil is predominantly generated in the Paleozoic. In the Sichuan Basin, oil was discovered in the Jurassic, and gas was mostly discovered in the Sinian and Triassic. Fourth, the western hydrocarbon zones are dominated by a "sandwich" multi-layer mode, such as the Junggar, Tarim, Qaidam basins. In summary, the theory of co-control of source and heat will be widely applied to oil and gas exploration all over China. Oil targets should be focused on the near shore areas in the southeastern China sea, the upper strata in the eastern and middle hydrocarbon zones, and the Ordovician, Permian and Paleogene strata in the western hydrocarbon zone, while gas targets should be focused on the off-shore areas in the southeastern China sea, the Cambrian, Carboniferous, Jurassic, and Quaternary strata in the western hydrocarbon zone. A pattern of exploring gas fields under or outside oil fields and oil fields under or outside gas fields is presented. Therefore, there is still a great prospect for oil and gas exploration in China.

Keywords: China; Onshore; Offshore; Oil and gas fields; Hydrocarbon source rock; Heat; Orderly; Theory of co-control of source and heat; Exploration areas

The tectonic setting in China and its neighboring areas exhibits a pattern of "three horizontal belts and four vertical belts" in the map (Fig. 1). "Three horizontal belts" refer to the Tianshan-Yinshan orogenic belt in the north, the Kunlun-Qilian-Qinling-Dabie orogenic belt in the middle, and the Nanling orogenic belt in the south. "Four vertical belts" refer to the Helanshan-Longmenshan-Hengduanshan orogenic belt in the west, the Greater Khingan Mountains-Taihangshan-Wuyishwangan orogenic belt in the middle, the Liaodong-Korean Peninsula-southeast coastal orogenic belt in the east, and the Diaoyu Island uplifted belt-Taishan Orogenic Belt-Philippine island arc belt-Borneo uplifted belt in the sea area. Three horizontal belts were formed at the end of the Hercynian, in the Indosinian and the Hercynian respectively from north to south, later these areas experienced multi-cycle activities, which represent major plate merging and re-orogenesis. The three vertical belts onshore are the product of intraplate deformation since the post-Indosinian, and the remaining offshore belt is the consequence of interaction between the Pacific Plate and the Asian Continent since the Late Eocene.

* Corresponding author.
E-mail address: lanlei@cnooc.com.cn (Lan L.).
Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2015.02.005

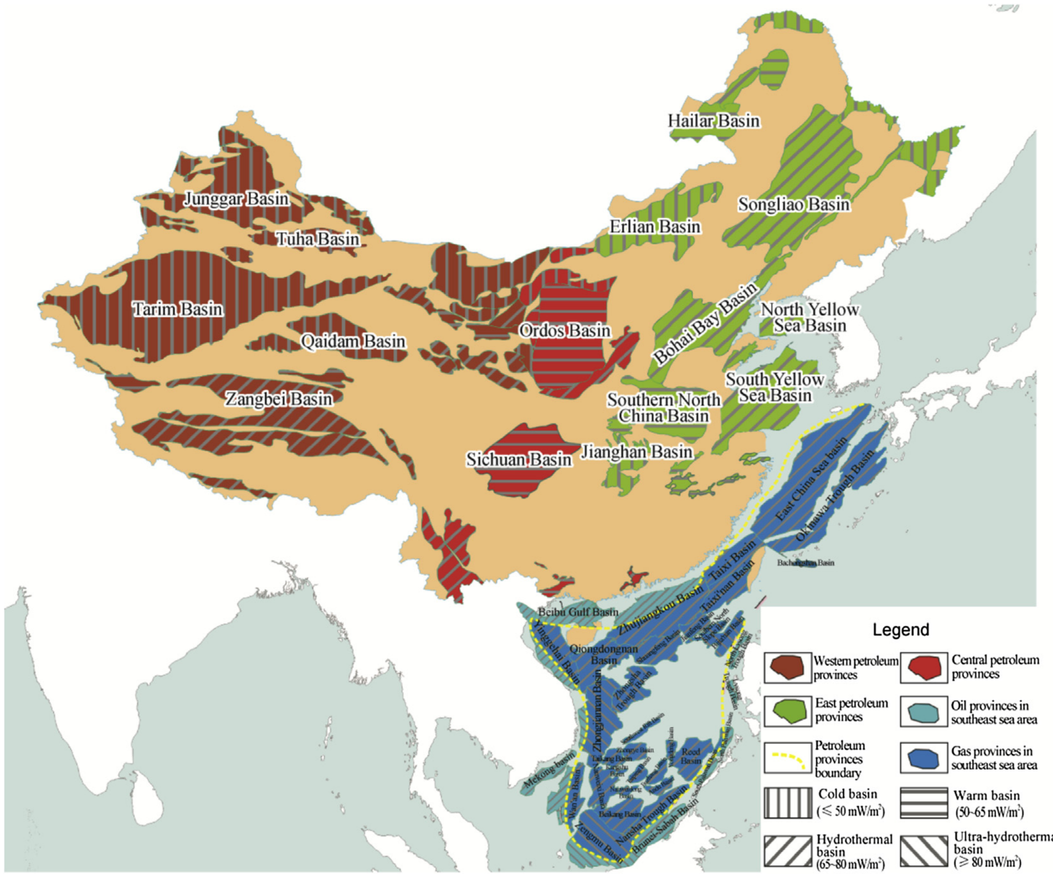

Fig. 1. Petroleum provinces in China.

Within this chessboard-like tectonic framework, there are depositional basin groups of different structural-geothermal mechanisms. Those basins in the East China Sea area and in the South China Sea area (the East China Sea Basin, the Taixi Basin, the Taixi'nan Basin, the Zhujiangkou Basin, the Beibu Gulf Basin, the Yinggehai Basin, the Qiongdongnan Basin, the Zhongjiannan Basin, the Wan'an Basin, the Zengmu Basin, the Brunei-Sabah Basin, etc.) are continental margin basins with young island arc fold belts as the basement, with high to extremely high heat flow and geothermal gradient at present, they represent the hydrothermal basin and ultra-hydrothermal basin. Those depositional basins lying between the Greater Khingan Mountains-Taihangshan-Wuyishan intraplate orogenic belt and Liaodong-Jiaodong-southeast coastal orogenic belt, including those multiphase basins (the Bohai Bay Basin, the Southern North China Basin, the Subei-South Yellow Sea Basin, and the Jianghan Basin) on the ancient crystalline basement and those fault-depression basins (the Songliao Basin and the Nanxiang Basin) growing on the Hercynian fold belt, belong to hydrothermal basins with high heat flow and geothermal gradient. The depositional basins between the Helanshan-Longmenshan-Hengduanshan orogenic belt and the Taihangshan-Wuyishan orogenic belt, including those multiphase basins (the Ordos Basin and the Sichuan Basin) on the ancient crystalline basement, belong to warm basins with medium heat flow and geothermal gradient at present. The onshore depositional basins to the west of the Helanshan-Longmenshan-Hengduanshan belt, including those multiphase basins on the ancient crystalline basement (the Tarim Basin) and at the fold belt (the Junggar Basin, the Tuha Basin and the Qaidam Basin), belong to cold basins with currently low heat flow and geothermal gradient.

Vertical hydrocarbon generation (including the conventional and the unconventional) patterns differ from basin group to basin group in China (Table 1). For example, the oil fields in the Ordos Basin contain gas in Paleozoic reservoirs and oil in Triassic-Jurassic reservoirs, and the oil fields in the Songliao Basin contain gas in Lower Cretaceous reservoirs and oil in Upper Cretaceous reservoirs. Other basins have orderly patterns of hydrocarbon distribution (Table 1). But at present there are few studies on the onshore and offshore petroleum generation and distribution in China considering the petroleum province (or basin group) to be a unit, so to figure out the distribution patterns of oil and gas fields in China and reveal their origins is of great significance for oil and gas field exploration.

As per the theory of "co-control of source and heat" [1,2], hydrocarbon generation is dependent on source rocks, the internal cause, and heat, the external cause. None of the causes is dispensable, and they work jointly to control whether there is hydrocarbon generated in a basin, the scale, phase state (oil or gas) and regional distribution pattern, as well as the orderly

Table 1
Hydrocarbon generation patterns of dominant source rocks in the petroleum provinces of China.

Epoch	West province			Central province		East province		Southeast sea area	
	Junggar	Tarim	Qaidam	Ordos	Sichuan	Songliao	Bohai Bay	Near-shore	Far-shore
Quaternary			Gas						
Neogene	Oil	Oil	Oil					Oil	Gas
Paleogene							Oil		
Cretaceous						Oil Gas			
Jurassic	Gas	Gas	Gas		Oil				
Triassic				Oil	Gas				
Permian	Oil			Gas			Gas		
Carboniferous	Gas								
Devonian									
Silurian									
Ordovician		Oil		Gas					
Cambrian		Gas							
Late Proterozoic									
Hydrocarbon generation pattern	Sandwich			Oil layers above gas layers				Near-shore oil and far-shore gas	

distribution of oil fields, gas fields and oil and gas fields in a petroleum province. The paper will look into the vertical onshore and offshore hydrocarbon generation patterns in China on the basis of co-control of source and heat.

1. Single hydrocarbon generation mode in southeast sea and its neighboring areas under the co-control of source and heat

The southeast coastal petroleum provinces in China include the East China Sea area and the South China Sea area, in which Indosinian and Yanshanian orogenic belts are the basement. Representing marginal sea basins, in fault depression and depression structures, these basins are mainly filled by Cenozoic formations (and residual Mesozoic basins locally). The source rocks in these basins are a set of Paleogene-Neogene formation of monotonous age [2–13], which generate different hydrocarbons in different basins. From the distribution of oil and gas fields, near-shore oil belt and far-shore gas belt can be discerned (Fig. 1 and Table 2).

1.1. Near-shore basins (or depressions)

Near-shore basins include the depressions in north Pearl River Mouth Basin, the Beibu Gulf Basin, the Mekong basin, the East Balingian Depression in south Zengmu Basin, south Brunei-Sabah Basin, etc. (Fig. 1). The source rocks in these basins are composed of medium-deep and deep lacustrine mudstones, transitional coal measures and marines mudstone [2–14]. These areas, located in hydrothermal basins, with source rocks in oil-generating windows and overburden of medium thickness, represent huge oil generation areas.

1.1.1. Depressions in north Pearl River Mouth Basin

The depressions in north Pearl River Mouth Basin (Figs. 2 and 3)lie on the continental shelf at northern South China Sea. With Yanshanian island arc belt as its basement, the Pearl River Mouth Basin evolved from a Paleogene fault subsidence to a Neogene depression and then entered the neotectonic period. It experienced extensive denudation at the end of Wenchang Fm in the Middle Eocene due to intense reconstruction. This basin has some secondary tectonic units, e.g. Zhu I Depression and Zhu III Depression, and tertiary tectonic units of more than ten sags and salients. These sags may be potential hydrocarbon-generating units, but most of them are separated by sub-salients into many sub-sags which are indeed the basic hydrocarbon-generating units. These subsags feature thick Paleogene formations and thin Neogene formations. The source rocks are composed of medium-deep lacustrine mudstone of the Eocene Wenchang Fm and limnetic coal measures of the Oligocene Enping Fm [3]; some sags may have residual Mesozoic marine to transitional source rocks. This area has a thermal gradient and heat flow value of 36.6 ± 6.0 °C/km and 66.1 ± 8 mW/m^2 respectively [15], representing a hydrothermal basin. The medium-deep Wenchang lacustrine mudstones buried within the range of oil-generating windows are the major oil source rocks in this area with a *TOC* (total organic carbon) content of 0.50%–4.88%, on average 1.22%, and the kerogen of sapropel hybrid type. Enping Fm generated a small amount of oil in the Zhu I Depression and some gas in the Zhu III Depression due the shallow buried depth and low thermal maturity. So in this area, only the Eocene Wenchang Fm is the major source bed and oil dominates in vertical sequences [3]. Discovered oil source sub-sags include Huizhou26 sub-sag, Lufeng13 sub-sag, Panyu4 sub-sag, Enping17 sub-sag, and Wenchang B sub-sag in the Zhu III Depression, etc. Vertically crude oil may occur in the basement assemblage, the lower assemblage of the Eocene Wenchang Fm and the Enping Fm, the middle assemblage of the Oligocene Zhuhai Fm and the Lower Miocene Zhujiang Fm, and the upper assemblage of the Middle Pliocene Yuehai Fm and the Wanshan Fm. So far most oil discovered in the north of the Pearl River Mouth Basin is in the middle assemblage due to intense neotectonic movement

Table 2
Hydrocarbon generation assemblages of "near-shore oil and far-shore gas" in China sea areas and their neighboring areas.

Province	Basin or depression	Source rock						Thermal maturity	Product	References
		Major source bed	Age	Sedimentary facies	Lithology	Mudstone *TOC*[a]	Kerogen	R_o		
Near-shore	North depression in the Pearl River Mouth Basin	Enping Fm	E_3	Limnetic, fluvial and swamp	Dark mudstone, carbargilite, and coal	2.68%–6.35%	Hybrid-humic	0.6%–1.3%	Oil	[3]
		Wenchang Fm	E_2	Medium-deep lacustrine	Dark mudstone	2.94%–26.87%	Sapropel-sapropel hybrid	0.9%–2.0%	Oil	[3]
	Weixi'nan Sag in the Beibu Gulf Basin	Liushagang Fm	E_2	Medium-deep lacustrine	Dark grey shale and dark mudstone	Shale: 3.07%–10.35%/6.23% Mudstone: 0.5%–4.3%/2.15%	Sapropel-sapropel hybrid	Mature	Oil	[3]
	The Mekong Basin	Chaxin Fm and upper Chaju Fm	E_3	Medium-deep lacustrine	Dark mudstone	Higher than 1% on the average and up to 20%	Hybrid	0.72%–1.3%	Oil	[4]
	East Balingian Depression in south Zengmu Basin	Lidi Fm	E_3	Coastal plain distributary channel	Mudstone and coal seams	Marine mudstone: 0.8%–2.2%	Sapropel hybrid-humic hybrid	Mature to highly mature	Oil	[5–8]
	South Brunei-Sabah Basin	Stage III–IV	N	Transitional to shallow marine	Black cat and carbonaceous shale	0.23%–5.87%	Humic	0.3%–0.68%	Oil	[9]
Far-shore	The East China Sea Basin	Huanggang Fm	E_3	Shallow lacustrine and shore to fluvial	Coal and carbargilite	Carbargilite and coal: 6.47%–75.68%	Humic hybrid	Mature	Gas	[3]
		Pinghu Fm	E_2	Limnetic to tide flat swamp	Coal and carbargilite	Carbargilite and coal: 6.55%–61.92%	Humic hybrid	Mature to highly mature	Gas	[3]
		Lingfeng Fm	E_1	Seashore to shallow marine	Dark mudstone	1.86%–2.65%/2.27%	Hybrid	Mature	Gas	[3,10]
		Yueguifeng Fm	E_1	Seashore to shallow marine	Brown and black mudstones	2.13%–3.75%/2.82%	Hybrid	Mature to highly mature	Gas	[3,10]
	The Baiyun Depression	Zhuhai Fm	E_3	Deltaic	Dark mudstone	0.4%–3.0%/1.1%	Humic	0.5%–2.0%, 2.8% in the major sub-sag	Gas	[3]
		Enping Fm	E_3	Deltaic-shallow marine	Dark mudstone, carbargilite and coal	0.7%–5.7%/1.8%	Humic hybrid and humic	0.8%–2.2% in the major sub-sag	Gas	[3]
		Eocene	E_2	Deep lacustrine to shore and shallow lacustrine	Dark mudstone	1.5%–4.9%/2.9%	Sapropel-sapropel hybrid	2.0%–3.8% in the major sub-sag, and 0.5%–1.8% in other areas	Gas	[3]
	The Qiongdongnan Basin	Huangliu Fm Meishan Fm Sanya Fm	N_1	Shallow marine-semi-deep marine	Mudstone	0.2%–1.1%/0.7%	Humic	Immature to post-mature	Gas	[11]
		Lingshui Fm Yacheng Fm	E_3	Strand plain swamp	Dark mudstone, carbargilite and coal	0.4%–2.5%/1.1%	Humic hybrid-humic	0.5%–2.5%	Gas	[11]
		Wenchang Fm	E_2	Lacustrine	Dark mudstone	1.6%–2.3%	Sapropel hybrid-sapropel	Highly mature to post-mature	Gas	[11]
	The Yinggehai Basin	Yinghuang Fm Meishan Fm Sanya Fm	N_1^2	Estuarine	Dark mudstone	0.4%–3.0%/1.3%	Humic	Mature to highly mature	Gas	[12]
		Lingshui Fm Yacheng Fm	E_3	Semi-closed bay and deltaic front	Dark mudstone, carbargilite and coal	0.4%–3.2%	Hybrid and humic	>4.0%	Gas	[12]

The Kangxi Depression in the	Xiwei Fm	E_3	Limnetic-estuarine	Dark mudstone, carbargilite and coal	0.4%–3.7%/0.9%	Hybrid-humic	0.5%–1.1%/0.8%	Gas	[13]
Wan'an Basin	Wan'an Fm Lizhun Fm	N_1	Seashore and shallow marine	Dark mudstone, carbargilite and coal	0.6%–0.9%/0.7%	Humic	0.4%–1.2%/0.7%	Gas	[13]
The Zengmu Basin	Haining Fm	N_1^2	Estuarine	Dark mudstone and marl	0.4%–1.9%	Hybrid-humic	Mature	Gas	[5–8]
	Lidi Fm	E_3-N_1	Transitional	Drub coal	Drub coal:0.69%–0.93%	Hybrid-humic	Mature to post-mature	Gas	[5–8]
North Brunei-Sabah Basin	Stage III–IV	N	Lower coastal plain, fluvial-marine and shelf deep marine	Black cat, carbonaceous shale, coaly siltstone and coal	0.15%–0.90%	Humic	Mature to post-mature	Gas	[9]

[a] For relevant parameters, data in the left of "/" presents the range of value, while data in the right of "/" presents the average value.

and active later oil migration, and other assemblages will be the focus in future exploration.

The exploration of the north depression in the Pearl River Mouth Basin began in the 1970s. After a batch of major oil fields were discovered in the 1980s, the discovery slowed down in the 1990s. To date, dozens of oil and gas fields and oil-gas structures have been discovered in the north depression and its neighboring areas, and proved probable and possible reserves in total exceed 10×10^8 t with more than 90 percent of oil and less than 10 percent of gas. Annual oil production has been more than 1000×10^4 t since 1996. Both theoretical analysis and exploration practice show that the north depression in the Pearl River Mouth Basin and its neighboring areas are all oil plays.

1.1.2. The Beibu Gulf Basin

The Beibu Gulf Basin, lying in the west part of the north continental shelf in the South China Sea, has experienced Paleogene fault subsidence, Neogene and Quaternary depression and neotectonic movement. The secondary units in the basin include three depressions and two uplifts, i.e. north depression, the Qixi Uplift, central depression, south uplift and south depression, and tertiary tectonic units include more than ten sags and salients [2,14] (Figs. 4 and 5). These sags are further separated into sub-sags which are the basic hydrocarbon-generating units, and most of which feature thick Paleogene and thin Neogene. The source rocks there are composed of medium-deep lacustrine mudstone in the Eocene Liushagang Fm, which, with mainly sapropelic and sapropel hybrid-typed organic matters [3] of high organic matter abundance, represent high-quality source rocks, but vary widely in distribution in various sub-sags. The Beibu Gulf Basin is a hydrothermal basin with a geothermal gradient and heat flow value of 32.9 ± 7.1 °C/km and 65.7 ± 8.9 mW/m^2 respectively. Source rocks of the second member of Liushagang Fm primarily generate oil due to the low thermal evolution degree, with R_o ranging from 0.2% to 1.2% [2,3]. Therefore, some sags in the basin, i.e. the Weixi'nan Sag (composed of three sub-sags), the Fushan Sag and the east sub-sag of the Wushi Sag, have been proved to be oil-rich due to the joint effect of source and heat. Vertically oil exists in the Carboniferous palaeo-buried hill assemblage, the lower assemblage of the Paleocene Changliu Fm and the Eocene Liushagang Fm, the middle assemblage of the Oligocene Weizhou Fm, and the upper assemblage of the Neogene Xiayang Fm and Jiaowei Fm. Most parts of the basin have experienced weak neotectonic movement since the Neogene Period [2,14] and petroleum accumulated near or within source beds. So far petroleum discoveries in the basin mainly have been concentrated in the middle and lower assemblages.

The exploration of the Beibu Gulf Basin began in the 1970s and bloomed after the 1980s. All oil fields discovered are multiple oil and gas reservoirs due to complex Paleogene fractures. So far, more than ten oil fields have been discovered in the basin with proved oil reserves of hundreds of millions of tons, and no independent gas reservoir with commercial value

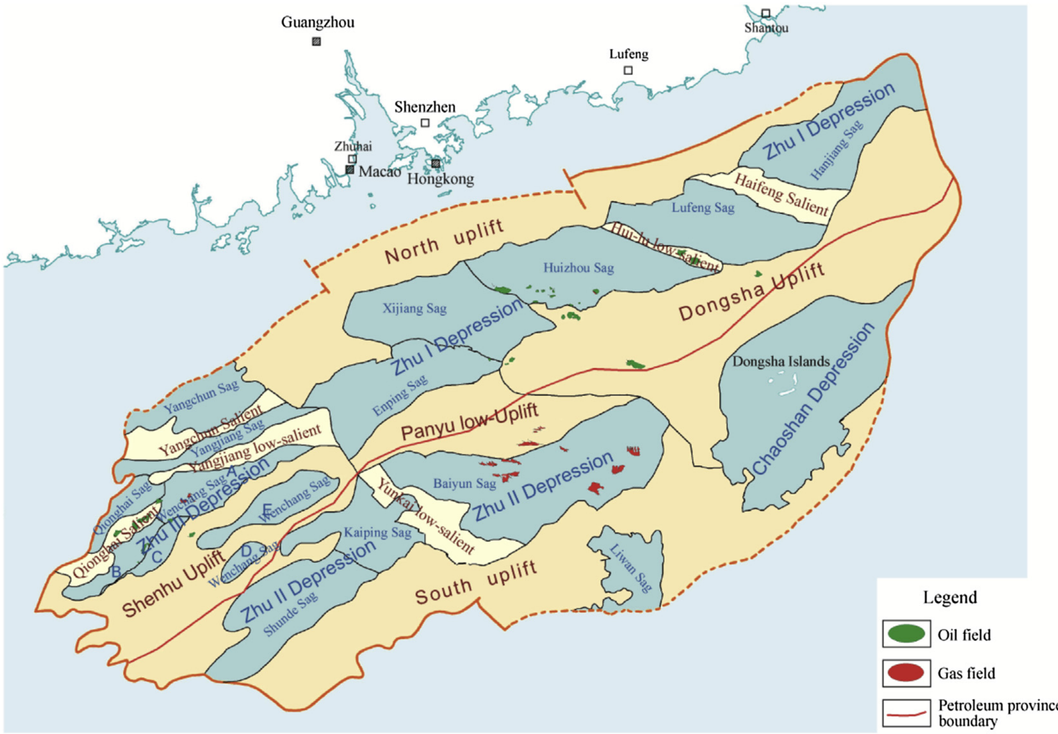

Fig. 2. Distribution of oil and gas fields in the Pearl River Mouth Basin.

has been discovered yet, indicating that the basin is of an oil type.

1.1.3. The Mekong Basin

The Mekong Basin is located in the south end of the continental shelf in western South China Sea. With Jurassic-Cretaceous granite, granodiorite and quartz diorite as basement, the basin has experienced Oligocene-Early Miocene fault subsidence, Middle Miocene strike-slipping and tectonic inversion, and Late Miocene regional depression. The Oligocene-Quaternary formations are the cap and the formations are up to 10 km thick in total. The basin consists of six secondary tectonic units, i.e. the west depression, the central depression, the northeast depression, the southeast depression, the northeast uplift and the east uplift. The major source rocks are middle to deep Oligocene lacustrine mudstone with a thickness of 100–600 m, *TOC* of 0.8%–1.6%, and organic matter of sapropelic and hybrid kerogens [4]. The basin has a thermal gradient of 31.3–34.1 °C/km and generally high heat flow value, which would be further enhanced locally by the radioactive decay of basement intermediate and acidic plutonic intrusive rocks. The source rocks, with a hydrocarbon generation threshold of 2000–3000 m, are in mature stage. Under the control of source and heat, the Mekong Basin is generating oil mainly, resulting in rich oil resources there.

The exploration of this basin began in the 1970s and to date at least 10 oil fields have been discovered, including Baihu, Shuguang, Heishi, Long, Jinqiangyu, etc., proving that the basin is of an oil type.

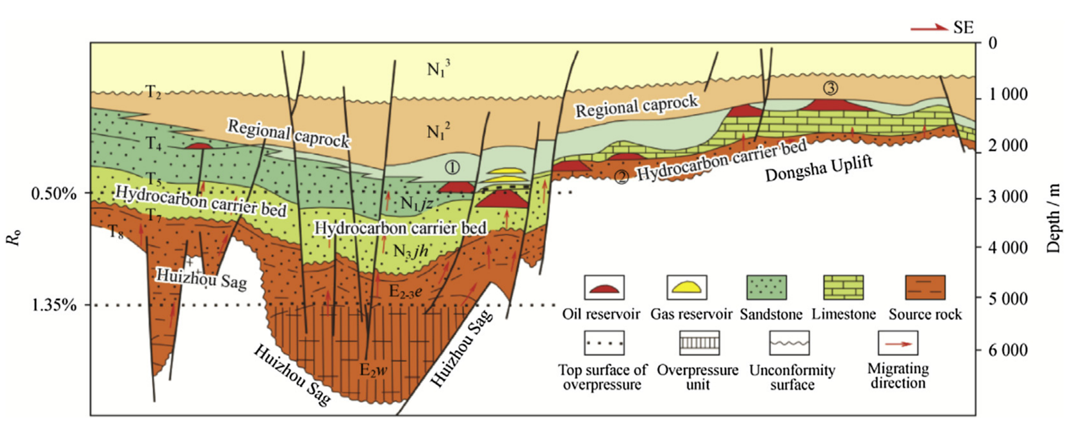

Fig. 3. Hydrocarbon migration pathway from the Huizhou Sag to the Dongsha Uplift in the north depression, Pearl River Mouth Basin [16].

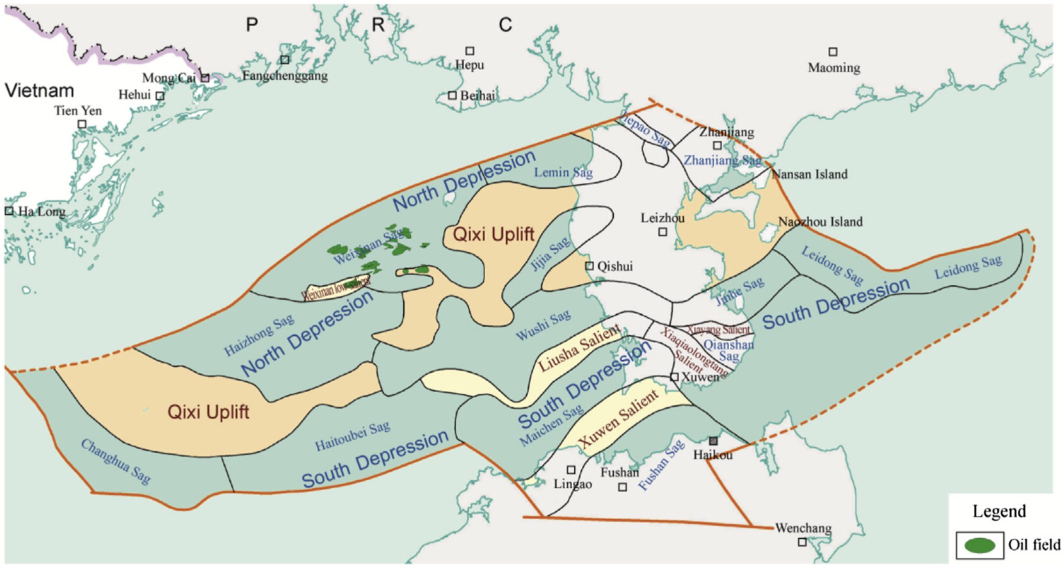

Fig. 4. Distribution of oil fields in the Beibu Gulf Basin.

1.1.4. The East Balingian Depression in the Zengmu Basin

The Zengmu Basin, in the west continental margin of southern South China Sea, with pre-Oligocene metamorphic rocks as basement, has multiphase deltaic basins under sustained compression since the Oligocene Epoch. There are eight secondary tectonic units, i.e. the East Balingian Depression, the Nankang Platform, the West Balingian Uplift, the Tatao Horst-Graben, the La'nai Uplift, the Suokang Depression, the Kangxi Depression and the West Slope [2,13]. In the East Balingian Depression in the southeast, source beds are coastal plain coal measures in the lower section of the Upper Oligocene and organic matter is mainly hybrid kerogen. Well drilling shows that the mudstone is tens of meters thick and coal-seam is more than 10 m thick. The coal seams with a *TOC* of 40%—80%, S_2 value (hydrocarbon production rate) of 40—194 kg/t and HI (hydrogen index) of 388—406 mg/g, have promising hydrocarbon generation capacity [5—8]. In spite of its shallow burial depth, the source rocks in the East Balingian Depression have an average heat flow value of 97 mW/m^2 and a thermal gradient of 33—68.4 °C/km, indicating that the basin is an ultra-hydrothermal one. The source rocks, having reached mature-highly mature stage, mainly produce oil.

The petroleum exploration in the Zengmu Basin started in the 1970s, have resulted in the discovery of nearly 10×10^8 t of oil reserves in the East Balingian Depression and minor gas yield, indicating that the depression is an oil-prone one.

1.1.5. The Brunei-Sabah Basin

The Brunei-Sabah Basin, lying in the east continental margin of southern South China Sea, is a fore-arc basin resulted from the subduction of Nansha Massif toward the Sunda Massif. The basement in the east (Brunei) is made up of folded deltaic plains of the Late Oligocene-the Early Miocene Meiligan Fm-the Maili'nao Fm-the Tanbulong Fm and deep shale, and folded abyssal flysch of the Late Eocene-the Early Miocene Crocker Fm in the west (Sabah). The cap is composed of Early or Middle Miocene-Quaternary formations. Cenozoic thickness in the basin is up to 12 km.

Miocene transitional coal measures constitute the main source rocks in the basin. The source rocks have a wide range

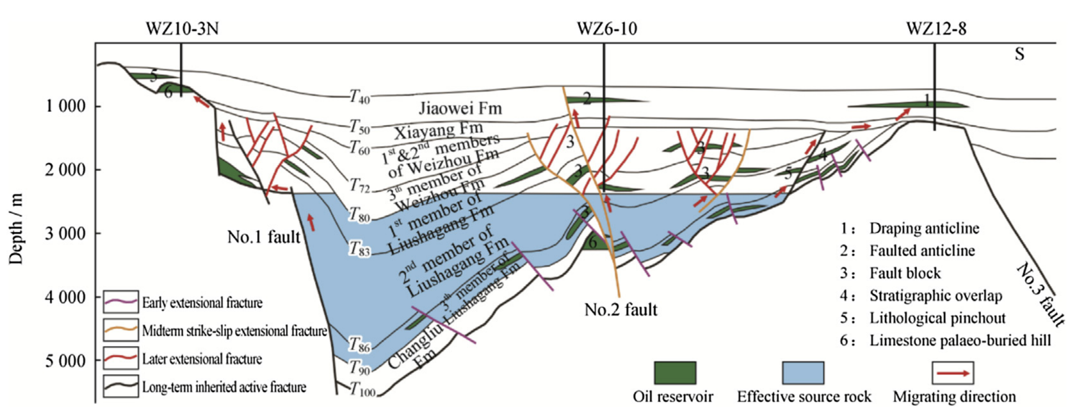

Fig. 5. Geologic section showing hydrocarbon accumulations in the Weixi'nan Sag, Beibu Gulf Basin [17].

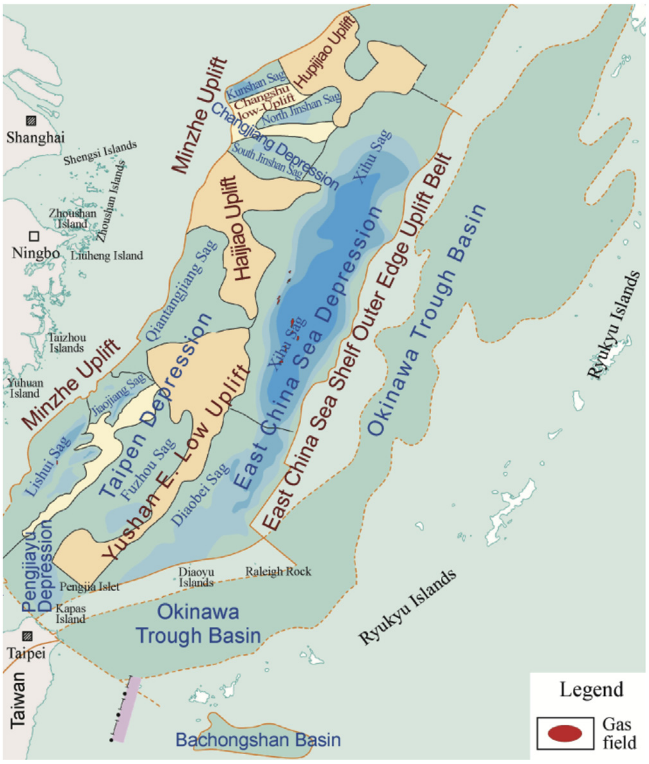

Fig. 6. Distribution of gas fields in the East China Sea Basin.

of total organic matter content (*TOC*) and the hydrocarbon generating index (HI) ranging from 0.15% to 90.00% and from 0.1 to 60.0 mg/g respectively, with poor to good hydrocarbon-generating potential, and organic matter of hybrid-humic type of kerogen [6–9]. The east part in the south (palaeo-subduction zone) is under distinct low heat flow background, with a thermal gradient of 18.2–32.5 °C/km. The source rocks, low mature to mature, mainly generate crude oil due to heat.

The petroleum exploration started from the end of the 18th century to the beginning of the 19th century, and hundreds of oil and gas fields have been discovered in the basin, mainly in the south-central part.

1.2. Far-shore basins (or depressions)

Far-shore basins include the East China Sea Basin, the Taixi Basin, the Taixi'nan Basin, the south depression in the Pearl River Mouth Basin, the Qiongdongnan Basin, the Yinggehai Basin, the Zhongjiannan Basin, the Wan'an Basin, the Kangxi Depression in the Zengmu Basin, and the north-central part of Brunei-Sabah Basin (Fig. 1).

1.2.1. The East China Sea Basin

The East China Sea Basin, located in the continental shelf of the East China Sea, with the Yanshanian continental margin as granite, experienced fault subsidence in the Paleocene-

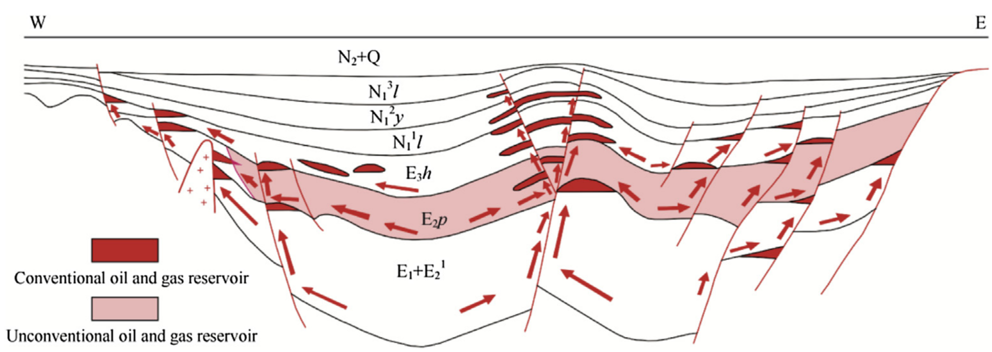

Fig. 7. Geologic section showing hydrocarbon accumulations in the Xihu Sag, East China Sea Basin.

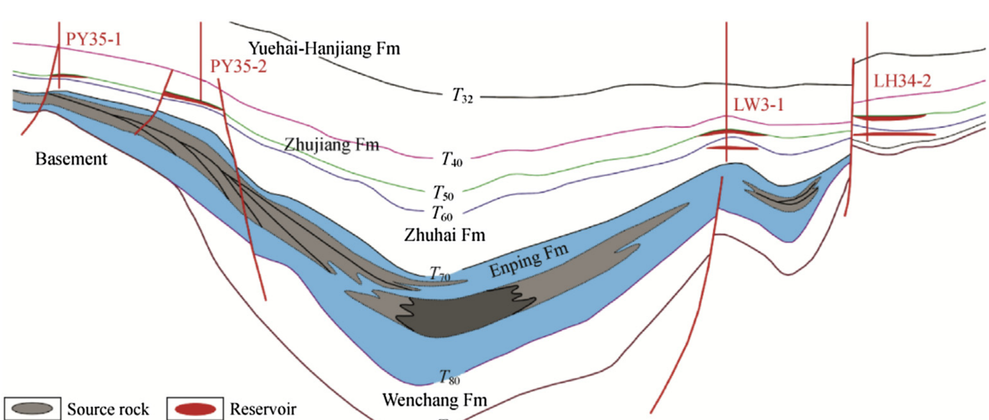

Fig. 8. Geologic section showing hydrocarbon accumulations in the Baiyun Sag, Pearl River Mouth Basin.

Eocene, depression in the Oligocene-Miocene and neotectonic movement in the Pliocene-Quaternary in Cenozoic Era. There mainly developed Cenozoic sedimentary formations from the Paleocene Series to the Quaternary System in the basin. The basin experienced five episodes of tectonic reworking and some tectonic inversions in particular (Figs. 6 and 7). There are two depressions and two uplifts in the basin, i.e. the west depression belt (the Changjiang Depression and the Taibei Depression), the central uplifted belt (the Hupijiao Uplift, the Haijiao Uplift and the Yushandong Uplift), the east depression belt (the Fujiang Sag, the Xihu Sag and the Diaobei Sag), and the east uplifted belt (the Diaoyu Island uplifted fold belt, i.e. the shelf break uplift). The basin is the product of back-arc spreading from the subduction of the Pacific Plate. With the underthrust zone retreating to the east, the basin experienced tectonic migration from west to east and shifting of depocenters eastwards, resulting in the differences in structure and depositional evolution from sag to sag. Paleocene fault subsidence mainly occurred in the west depression belt and Eocene-Oligocene fault subsidence in the east depression.

In this basin, the Paleocene Series is composed of lacustrine mudstone, transitional coal measures and marine mudstone; the Eocene Series consists of transitional coal measures and estuarine mudstone. Coal measures composed of coal seams, carbargilite and dark mudstone are the major source rocks in the basin. Coal seams of the Eocene Pinghu Fm were encountered in 16 exploratory wells, with an average thickness of coal seams in each individual well of 16.9 m, single-layer thickness of 0.3−1.2 m in general and the maximum cumulative thickness of 50.6 m. The maximum cumulative thickness of coal seams and carbargilite is 75.8 m and the cumulative thickness of dark mudstone is 200−1800 m. Pinghu dark mudstone is medium to high in organic matter abundance, with a maximum *TOC* of 1.97%. Coal seams have high abundance of humic hybrid-humic-typed organic matter, *TOC* of up to 57.07%; coal-measure source rocks contain some hydrogen-rich maceral [3,14]. Coal-measure source rocks mainly occur in deltaic plains and coastal plains and tectonically in the west and north of the Xihu Sag [18].

The thermal gradient in the basin and its surrounding areas, low in the north and high in the south, is 25−43.5 °C/km, and 32.7 °C/km on average. The heat flow value is high in the east and low in the west. As a result, most source rocks at the bottom of the Yueguifeng Fm in the Jiaojiang Sag in the west part of the basin have matured with $R_o > 0.7\%$ and entered the oil-generating window. Most source rocks in sub-sags have entered the wet gas window with $R_o > 1.3\%$, and some deep source rocks have entered the dry gas window with $R_o > 2.0\%$. In comparison, the east depression belt in the basin contains source rocks with relatively high maturity. For example, most source rocks at the bottom of the Pinghu Fm in the Xihu Sag have entered the dry gas window with $R_o > 2.0\%$ [18,19]. The basin mainly generates natural gases under the co-control of source and heat. There are several reservoir-seal assemblages in the basin, namely, the basement assemblage, Mesozoic assemblage, and Paleocene, Eocene, Oligocene and Miocene assemblages, in which Eocene and Oligocene assemblages are main reservoir-forming ones. The basin experienced several episodes of tectonic inversions, so reverse anticlines are the major trap type.

The petroleum geologic survey in the East China Sea Basin began in the 1970s and Pinghu oil and gas field was discovered in the 1980s. To date, a number of gas fields have been

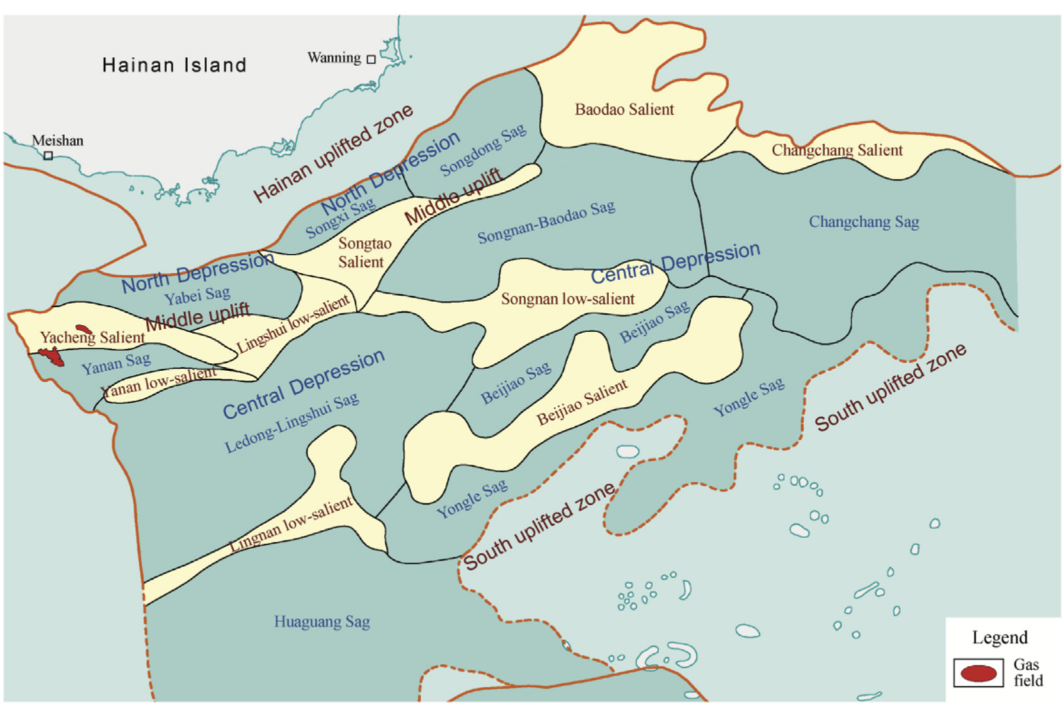

Fig. 9. Distribution of gas fields in the Qiongdongnan Basin.

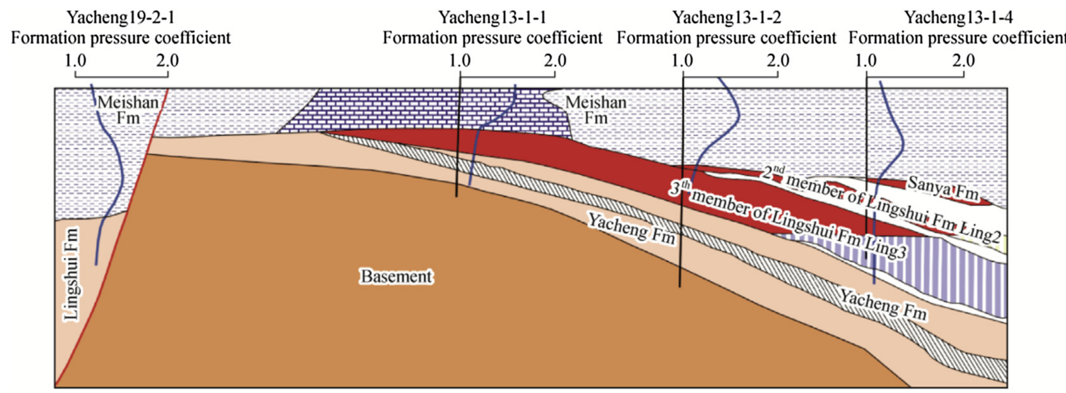

Fig. 10. Gas reservoir section across the Yacheng13-1 gas field in the Qiongdongnan Basin [21].

discovered in the Xihu and Lishui sags, demonstrating that the basin is rich in gas.

1.2.2. Baiyun Sag in the Pearl River Mouth Basin

The Pearl River Mouth Basin is located in the east continental margin of northern South China Sea, and the Baiyun Sag is in the Zhu II Depression in the south depression belt of the basin. With Yanshanian island arc belt as its basement, the sag has mainly Cenozoic formations. The sag has experienced Paleogene fault subsidence, Early and Middle Miocene depression and neotectonic movement since the Late Miocene [20]. There are three sets of source rocks, i.e. medium-deep lacustrine mudstone of the Eocene Wenchang Fm, transitional coal measures and estuarine mudstone of the Lower Oligocene Enping Fm, and marine mudstone of the Upper Oligocene Zhuhai Fm (Fig. 8). Enping transitional coal measures and estuarine mudstone are the major source rocks in the sag; the dark mudstone with *TOC* of 1.0%–1.5%, and wide distribution, has mainly kerogen of humic hybrid and humic types. With an area of over 5000 km^2, Enping coal-measure source rocks mainly occur in the slope area in the north of the sag. Well PY 33-1-1 encountered 20 coal seams in the Enping Fm with a cumulative thickness of 22.98 m [18]. The medium-deep lacustrine source rocks of the Wenchang Fm have a *TOC* of 0.50%–4.88%, and 1.22% on average, and mainly sapropel hybrid type of kerogen. The Baiyun Sag, located in the ocean-land transitional zone, is an ultra-hydrothermal basin with a thermal gradient and a heat flow value of up to 4.5 °C/100 m and 77.5 mW/m^2 respectively [15]. The source rocks at the bottom of the Enping Fm in the Baiyun Sag currently have R_o of 0.5%–2.0% in the center of the sag, 2.0% at the innermost of the main sag, and 0.5%–0.7% in the margin of the sag. Organic matter is in mature- and highly-mature stages, so it mainly generates gas and a small amount of light oil and condensate oil. The source rocks mainly produce natural gas in the main sub-sag, and crude oil in those surrounding sub-sags because of shallower burial depth. In addition, Wenchang Fm source rocks in the slope zone have also entered gas window with a R_o of 2.1%. Oil and gas have been discovered in Oligocene and Neogene reservoir-cap assemblages in the Baiyun Sag and its surrounding areas. So far petroleum exploration and discoveries mainly concentrate in the Zhujiang Fm. The Enping and Zhuhai Fms are anticipated to be the major reservoir-cap assemblages.

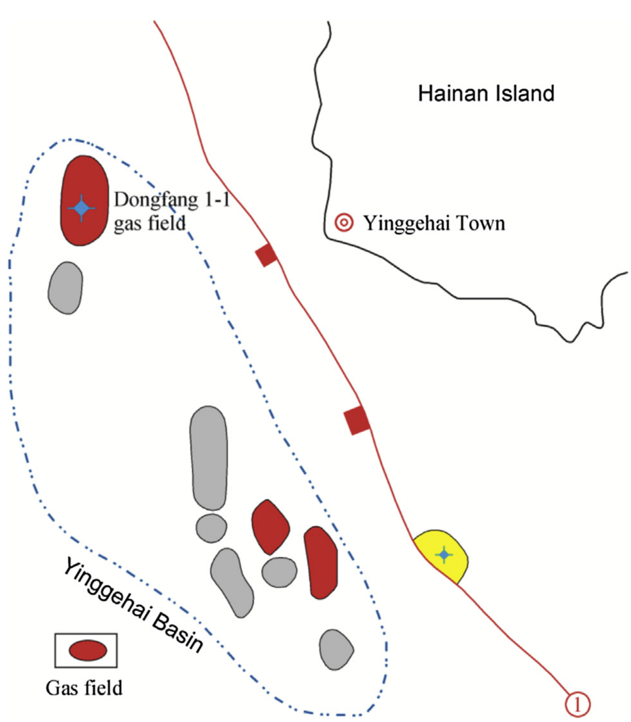

Fig. 11. Distribution of gas fields in the Yinggehai Basin.

Petroleum exploration in the Baiyun Sag and its surrounding areas began in the 1970s, followed by the first commercial discoveries in 2002 and a milestone discovery in deep water in 2006. The major discoveries in this area so far are gas fields and gas-bearing structures (e.g. Liuhua29-1, Liuhua34-2, and Liwan3-1), indicating that the Baiyun Sag is rich in hydrocarbon and mainly generates gas.

1.2.3. The Qiongdongnan Basin

The Qiongdongnan Basin lies in the west continental margin of northern South China Sea where the basement is Yanshanian island arc belt intercalated with Proterozoic crystalline massifs. After Paleogene fault subsidence, Neogene depression and neotectonic movement, the basin exhibits a

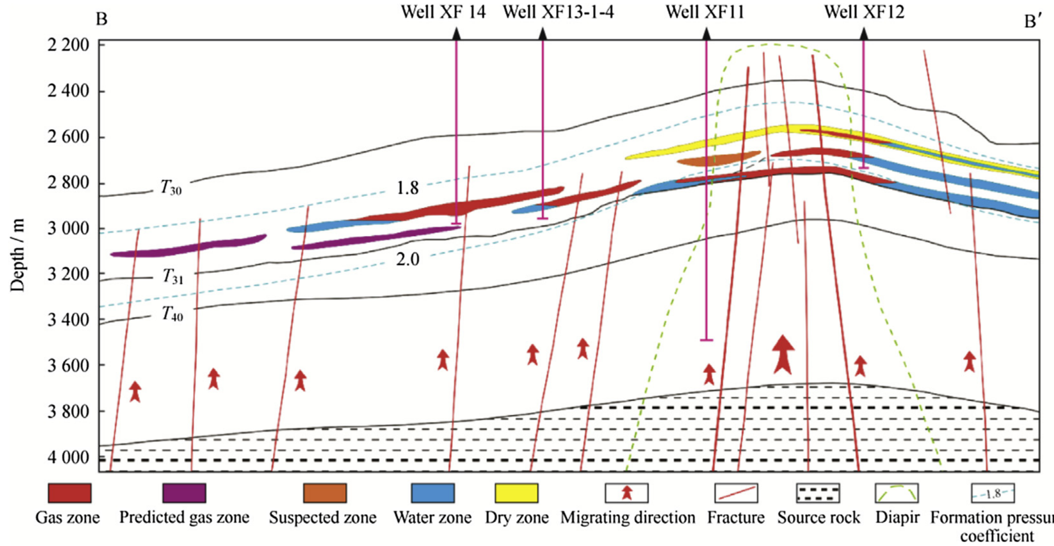

Fig. 12. Geologic section showing high temperature and overpressure natural gas accumulation mode in the Yinggehai Basin [22].

tectonic pattern of fault depression and depression and is separated into a north depression, a central uplift and a south depression (Fig. 9). During fault subsidence, the Eocene Series was deposited in a continental lake basin. The Oligocene Yacheng Fm was deposited in semi-closed estuarine and shallow sea, and the Lingshui Fm in littoral and shallow sea. Afterward the Neogene and Quaternary Systems deposited are epicontinental, shelf and aktian deposits. Three sets of source rocks occur in the basin, i.e. Eocene lacustrine mudstone, Lower Oligocene Yacheng transitional coal measures and Upper Oligocene Lingshui shallow-sea–bathypelagic mudstone (Fig. 10). The major source bed is the Yacheng Fm, which is divided into three members from the bottom up, i.e. the 3rd member composed of braided river deltaic deposits, the 2nd member of lagoon deposits and the 1st member of tide flat deposits. All the three members contain coal measures and marine mudstone [14,18]. Coal measures mainly occur in braided rive deltas and tidal flats in those gentle half-graben slope zones, followed by fan deltas and tidal flats in steep slope zones, and dark mudstone mainly occurs in lagoons in deep trenches. Coal seams drilled in more than 10 wells mostly occur in deltaic plains and tidal flats and are characterized by multiple beds, small thickness and inconsistent lateral extension. At most 35 coal beds were interpreted in an individual well, 12 beds in the 3rd member, 7 in the 2nd member and 16 in the 1st member. On average 10 coal beds were interpreted in the 3rd, 4 in the 2nd and 9 in the 1st. The *TOC* of coal beds and dark mudstone are 32.37%–81.30% and 0.24%–5.25% respectively and the kerogens are mainly of hybrid-humic types [3]. For example, the Yacheng Fm in Well YC 13-1-2 has *TOC* of 1%–4% and some carbargilite and coals have *TOC* of 20%–40%. The *TOC* of Yacheng dark mudstone in Well YC 21-1-4 is about 1%. With a thermal gradient of 25.2%–60.8 °C/km, and 36.6–39.1 °C/km on average, the Qiongdongnan Basin is a hydrothermal basin [15]. Source rocks in the basin have entered highly mature and post mature stages due to a deep buried depth and maintained a heat flow value of over 70 mW/m^2 resulted from basin extension after Yacheng Fm deposition. For example, the main source rocks in the Ledong-Lingshui Sag have a R_o value of over 2.0%. Natural gas would dominate over hydrocarbon generation under these source and heat conditions. There are three reservoir-cap assemblages, i.e. basement assemblage, Paleogene assemblage and Neogene assemblage. So far oil and gas discoveries have been made in them except in the basement assemblage.

The exploration of the basin began at the end of the 1970s, and some gas fields and gas-bearing structures (e.g. Yacheng13-1, Yacheng21-1 and Lingshui22-1) have been discovered. It is inferred that the Qiongdongnan Basin is a gas-typed basin mainly producing natural gas.

1.2.4. The Yinggehai Basin

The Yinggehai Basin, lying at the junction of the north continental margin and west continental margin of the South China Sea (Figs. 1, 11 and 12) on an indosinian fold belt basement, is a large deep basin in northwest direction of high temperature resulted from Cenozoic strike slipping and extension, which is divided into the Yingdong Slope, the Yingzhong Depression and the Yingxi Slope. The Paleogene System in Yingzhong Depression was composed of three sags in the north, middle and south, which merged into a large sag in the Neogene and Quaternary, and in the center of the depression developed Neogene diapiric structures (Figs. 11 and 12). The Huangliu mudstone has *TOC* of 0.39%–2.60%, and 1.06% on average; The Meishan thick mudstone has *TOC* of 0.44%–3.17%, and 1.45% on average; both of them have kerogen of humic hybrid and humic types [12]. It is inferred that the Middle Miocene Meishan Fm is the major source bed in the basin. Meanwhile, it is concluded from geotemperature data and rock thermophysical properties from well drilling that the basin is a hydrothermal one with a high temperature. The

Table 3
Hydrocarbon generation pattern of "upper oil and lower gas" in east China petroleum provinces.

Basin	Source rock								Thermal maturity	Product	References
	Major bed	Age	Region	Sedimentary facies	Lithology	Kerogen type	Mudstone *TOC*	Mudstone $S_1 + S_2$/(mg g^{-1})	R_o		
Songliao	Nen1 and Nen2	K_2	Central Depression	Fluvial, deltaic, shore lake and shallow lacustrine	Dark mudstone	Sapropel-hybrid	0.1%−13.7%/2.1%	0.1−117.3/9.3	0.2%−1.3%	Oil	[25]
	Qingshankou Fm	N_2	Central Depression	Shallow to deep lacustrine	Dark mudstone and oil shale	Sapropel-hybrid, some humic	0.5%−10.8%/3.1%	0.1−13.1/1.6	0.4%−1.4%/0.9%	Oil	[26]
	Deng2	K_1	Central Depression	Deep-shallow lacustrine and shore lake	Mudstone	Humic	0.1%−0.8%/0.2%	0.1−0.4/0.1	Highly mature	Gas	[27]
	Yingcheng Fm	K_1	Controlled by fault subsidence	Shore lake, shallow lacustrine and fan delta	Dark mudstone and some coals	Humic	0.1%−6.5%/1.3%	0.1−12.6/1.3	Generally >2%	Gas	[28]
	Shahezi Fm	K_1	Controlled by fault subsidence	Fluvial fan−fan delta-semi-deep lacustrine	Dark mudstone and coal streaks	Humic	0.2%−9.3%/2.0%	0.1−14.1/1.	Post mature	Gas	[28]
	Huoshiling Fm	J_3	Controlled by fault subsidence	Deep-shallow lacustrine	Dark mudstone and some coals	Humic hybrid-humic	0.1%−5.8%/2.0%	0.10−14.71/0.77	Post mature	Gas	[28]
Bohai Bay	Dong3	E_2	Bozhong Depression	Lacustrine	Dark mudstone	Hybrid, some humic	0.8%−2.7%/1.8%	5.5−15.4/11.3	0.3%−0.9%	Oil	[29]
	Sha1 and Sha2	E_2	Controlled by fault subsidence	Lacustrine	Dark mudstone and oil shale	Hybrid, some sapropel	0.5%−7.0%/2.8%	0.4−59.8/12.	0.3%−2.0%	Oil	[29]
	Sha3	E_2	Controlled by fault subsidence	Lacustrine	Dark mudstone and some carbargilite	Mainly hybrid	0.5%−5.1%/2.4%	0.6−86.9/11.	0.3%−3.0%	Oil	[29]
	Sha4	E_2	Controlled by fault subsidence	Lacustrine	Dark mudstone	Sapropel hybrid-humic hybrid	0.5%−7.8%/2.1%	0.5−60.6/11.3	Liaodong Bay: 0.4%−1.3%	Oil	[29,30]
	Benxi Fm Taiyuan Fm Shanxi Fm	C-P	Residual	Transitional	Coal, carbargilite and dark mudstone	Coal: hybrid; carbargilite: humic hybrid; mudstone: humic	0.65%	Coal: 111.5 Carbargilite: 35.5 Dark mudstone: 3.1	0.5%−1.8%	Gas	[31,32]
	Benxi Fm Taiyuan Fm Shanxi Fm	C-P	Residual	Transitional	Dark mudstone, coal and carbargilite	Humic	Carbargilite: 16.6% Mudstone: 1.9%		Mature to post-mature	Gas	[33,34]
	Benxi Fm Taiyuan Fm Shanxi Fm	C-P	Residual	Transitional	Dark mudstone, carbargilite and coal	Humic	Coal: 60% Mudstone: 2%−3%		0.7%−1.6%	Gas	[35]

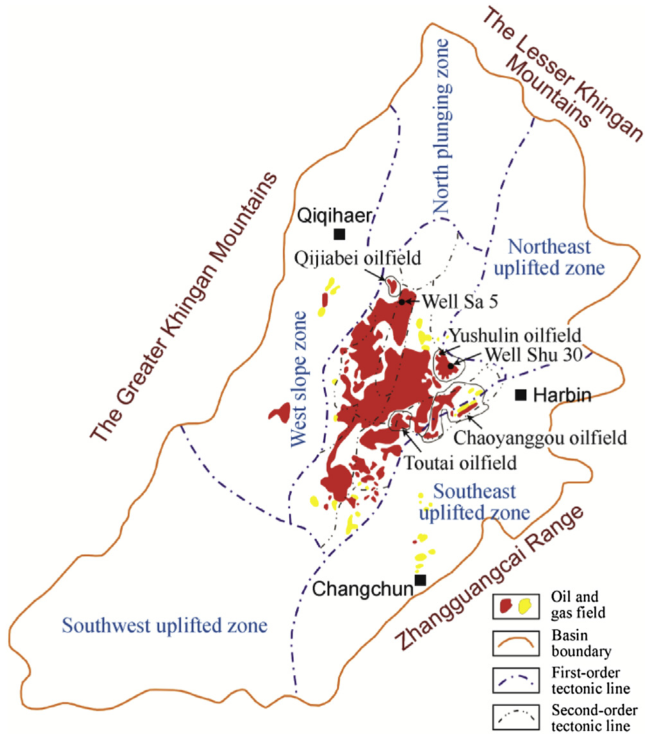

Fig. 13. Distribution of oil and gas fields in the Songliao Basin [36].

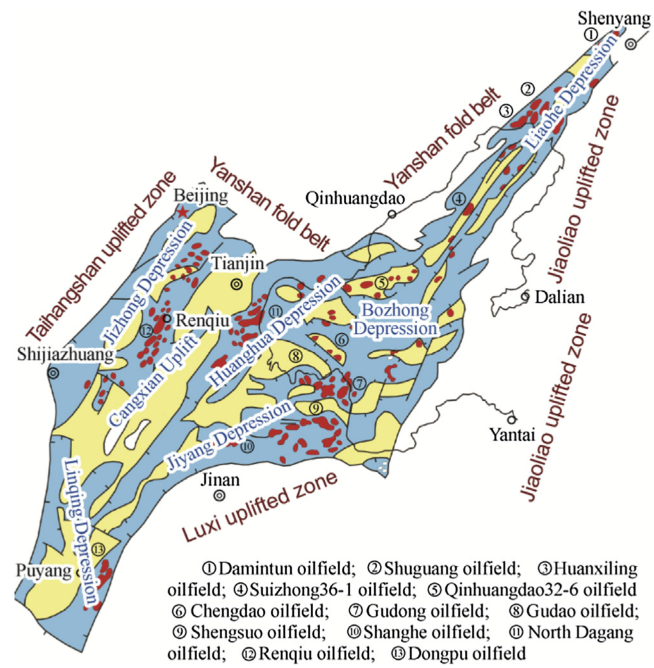

Fig. 15. Distribution of oil fields in the Bohai Bay Basin.

thermal gradient in the central depression is higher than 50.0 °C/km (the average thermal gradient is 45.0 °C/km). Analysis of $\delta^{13}C_1$ value shows Ro of shallow gas layers is generally higher than 1.2%, indicating a highly-mature–post-mature stage. Under the co-control of source and heat, the basin mainly produces natural gas, which distributes mostly in Pliocene Yinggehai anticlinal structures in shallow diapiric zones of normal temperature and pressure, and also in the Upper Miocene Huangliu Fm of high temperature and pressure.

Petroleum exploration in the Yinggehai Basin started in the 1950s and some gas fields have been discovered in the anticlinal and lithologic traps in the central anticlinal zone in the Yingzhong Depression, among which Dongfang1-1 and Dongfang13 gas fields (including Dongfang13-1 and Dongfang13-12) are all large gas fields of a hundred billion cubic meter magnitude. It has been demonstrated by exploration and research findings that the Yinggehai Basin is a gas-typed basin.

1.2.5. The central depression in the Wan'an Basin

The Wan'an Basin lies in the south continental margin of western South China Sea on the basement of Indosinian fold system. The basin has experienced extension from the Oligocene Epoch to the Early Miocene, Middle Miocene strike slipping and torsion, and regional depression from the Pliocene Epoch to the Quaternary Period. The basin consists of 10 secondary tectonic units, i.e. the west depression, southwest slope, northwest fault bench, north depression, north uplift,

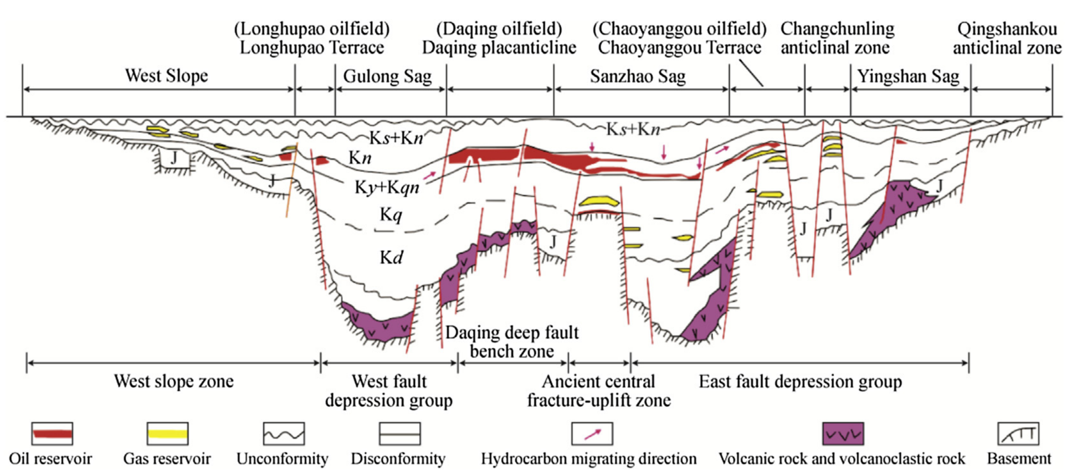

Fig. 14. Geologic section showing hydrocarbon accumulation in the Songliao Basin [41].

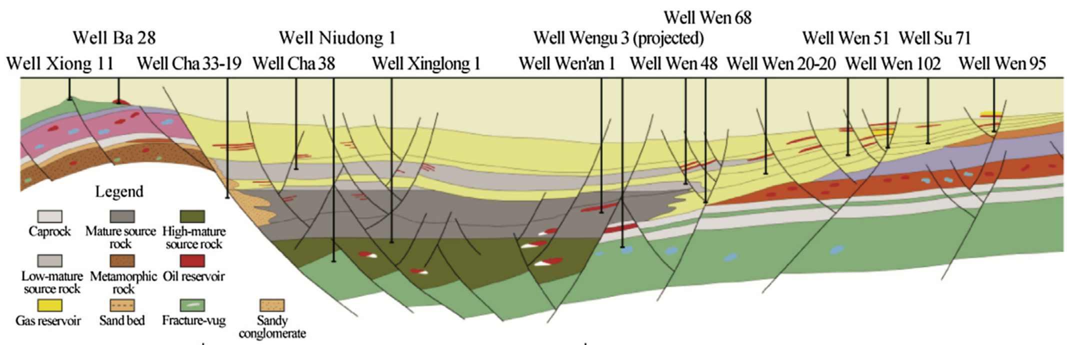

Fig. 16. Geologic section showing hydrocarbon accumulation in the Baxian Sag, Bohai Bay Basin [32].

middle depression, middle uplift, south depression, east uplift and east depression [23]. There are three sets of source rocks in the basin, i.e. Oligocene, Lower Miocene and Middle Miocene, among which the Oligocene and the Lower Miocene are the major source beds. Oligocene source rocks, mainly carbargilite and mudstone, have *TOC* of over 1% and mostly between 1% and 10%, and kerogen of hybrid and humic types. Lower Miocene source rocks, mainly mudstone, have *TOC* of about 1% and 1%–10% in local areas, and kerogen mainly of hybrid and humic types. The depression has a heat flow value of 24.22–121.00 mW/m^2, and 71.90 mW/m^2 on average. Oligocene source rocks have a Ro value of 1.3%–2.5%, indicating high maturity to post maturity. Lower Miocene source rocks have a Ro value of 0.7%–2.1%, indicating a mature–highly-mature stage. It is concluded from comprehensive analysis of heat and source rock conditions that Lower Miocene and Oligocene mature source rocks rich in organic matters are the major source rocks in the basin and mainly generate natural gas. There are several source-reservoir-cap assemblages in the basin, namely, the basement assemblage, Oligocene assemblage, Miocene assemblage and Pliocene assemblage etc.

The exploration of the Wan'an Basin started in the 1970s, and nearly 30 oil and gas fields have been discovered, most of which are gas fields, indicating that the basin is a gas-typed one.

1.2.6. The Kangxi Depression in the Zengmu Basin

The Zengmu Basin lies in the west continental margin of southern South China Sea, in the north of which Kangxi Depression is located. It is a large deep depression with Cenozoic of up to 15 km thick. The source rocks there include Oligocene and Lower and Middle Miocene coal measures and marine mudstone. Oligocene and Lower Miocene source rocks are transitional trub with *TOC* of 0.69–0.93% and kerogen of hybrid and humic types. The organic matter is getting higher in abundance and better in types toward the depression center, reaching medium–good gas-generating capacity. Coal beds contain 25 percent of waxy humic compounds which would generate oil and gas. In Miocene marine mudstone source rocks, the organic matter is hybrid-typed and humic-typed kerogens which have already entered hydrocarbon-generating window [9,24]. The Kangxi Depression lying in continental shelf and slope zone has a high thermal gradient and heat flow value, where the source rocks buried deep and subjected to strong heat effect, have entered a post-mature stage, and mainly generate natural gas, so the Kangxi Depression is a huge natural gas province.

Up to now natural gas reserves of trillions of cubic meters and more than one hundred oil and gas fields have been discovered in the Kangxi Depression and its neighboring areas. The proved oil and gas reserves are huge and natural gas reserves account for 85 percent of the total.

2. Double hydrocarbon generation mode of “upper oil and lower gas” in East China under the co-control of source and heat

Onshore petroleum provinces in East China include Jilin and Heilongjiang Mesozoic and Cenozoic rifts in Northeast China (including the Songliao Basin, the Haila'er Basin, the Erlian Basin, the Dayangshu Basin, the Sanjiang Basin etc. formed in the Late Jurassic-Cretaceous; only the Yilan-Yitong Graben System formed in the Paleogene Period.), the Bohai Bay Basin (including the Xialiaohe Depression, the Liaodong Gulf Depression, the Bozhong Depression, the Jiyang Depression, the Huanghua Depression, the Jizhong Depression, the Linqing Depression, the Chengning Uplift, the Cangxian Uplift, the Neihuang Uplift, etc. mostly formed in the Paleogene Period), the Southern North China Basin, the Nanxiang Basin, the Jianghan Basin, the North Yellow Sea Basin, the Northern Jiangsu – South Yellow Sea Basin, etc. (Fig. 1). Seated on the craton or Hercynian-Indosinian fold basement, these basins with different origins were formed in different stages and experienced various reconstruction. Most of them are residual superimposed basins, i.e. some residual basins with different origins superimposed together with various source rocks (Table 3). Under the dual control of regional heat flow field and burial, source rocks have experienced different heat effects, so lower source beds primarily generate gas and upper source beds generate oil, presenting a “lower gas and upper oil” hydrocarbon generation mode. For example, the Lower Cretaceous produces natural gas and the Upper Cretaceous crude oil in the Songliao Basin. Similarly in

Table 4
Hydrocarbon generation pattern of "upper oil and lower gas" in central China petroleum provinces.

Basin	Source rock							Thermal maturity	Product	References
	Major source bed	Age	Region	Sedimentary facies	Lithology	Kerogen	Mudstone *TOC*	R_o		
Ordos	Yan'an Fm	J_1	South basin	Fluvial and limnetic	Black mudstone and coal seams	Humic and humic hybrid	0.2%−3.0%/1.1%	0.7%−0.8%	Oil	[42]
	Yanchang Fm	T_3	South basin	Inland and lacustrine	Mudstone, carbargilite and oil shale	Oil shale: sapropel hybrid; mudstone: humic hybrid; carbargilite: humic	0.1%−36.8%/4.6%	0.4%−1.2%/0.8%	Oil	[43,44]
	Shanxi Fm	P_1	Whole basin	Transitional	Coal seams and dark mudstone	Humic hybrid and humic	1.2%−2.8%/2.3%	2.6%−2.7%	Gas	[44−46]
	Benxi Fm Taiyuan Fm	$C_{2\text{-}3}$	Whole basin	Transitional	Coal seams and dark mudstone	Humic hybrid and humic	Benxi: 0.4%−6.7%/2.5% Taiyuan: 1.3%−3.6%/2.3%	Benxi: 2.6%−2.8% Taiyuan: 2.67%	Gas	[44−46]
	Majiagou Fm Pingliang Fm	O	Whole basin	Marine	Argilliferous and argillaceous carbonate rocks	Sapropel hybrid and sapropel	0.3%	0.7%−3.0%	Gas	[44,47]
	Changshan Fm Gushan Fm	€	West and south margin	Marine	Carbonate rocks	Sapropel hybrid and sapropel	Carbonate rock: 0.13%	1.5%−3.4%	Gas	[44,47]
Sichuan	Ziliujing Fm-Lianggaoshan Fm	J_1	Central and North Sichuan	Deep lacustrine and semi-deep lacustrine	Dark mudstone	Hybrid and sapropel	Ziliujing: 1.27% Lianggaoshan: 0.92%	0.65−1.69%; mostly 1.0% in Central Sichuan	Oil	[48]
	Xujiahe Fm	T_3	West and Central Sichuan	Lacustrine and fluvial	Dark mudstone sandwiched with coal seams	Humic	1.6%−6.4%	Mature to highly mature	Gas	[49,50]
	Feixian'guan Fm	T_1	East basin	Marine	Argillutite and carbonate rock	Sapropel hybrid, humic hybrid and humic	Carbonate rock: 0.1%−0.6%/0.3%	1.4%−2.8%	Gas	[51]
	Wujiaping Fm	P_2	Northeast Sichuan	Marine	Black shale and marl	Sapropel hybrid	0.5%−10.4%/2.0%	Highly mature to post mature	Gas	[52,53]
	Longtan Fm	P_2	Central Sichuan and area on the south	Transitional	Carbonate rock, black shale and coal measures	Sapropel, hybrid and humic	?-10%/4.5%	0.9%−3.4%	Gas	[52,53]
	Qixia Fm Maokou Fm	P_1	South Sichuan	Plateau	Carbonate rock and mudstone	Sapropel and hybrid	Mudstone: 3.5% Carbonate rock: 0.8%	1.2%−2.0%	Gas	[52,53]
	Longmaxi Fm	S_1	East Sichuan	Continental shelf	Dark mudstone and black shale with graptolite	Mainly sapropel	0.4%−3.1%/0.8%	2.4%−3.6%/2.8%	Gas	[54,55]
	Wufeng Fm	O_3	Changning County	Continental shelf	Carbonaceous shale and carbargilite	Sapropel and hybrid	2.1%−7.6%/4.1%	1.49%−3.13%	Gas	[49]
	Qiongzhusi Fm Jiulaodong Fm	$€_1$	Whole basin	open sea continental shelf	Argillite and carbonate rock	Mainly sapropel	0.3%−4.2%/0.6%	Generally above 2.5%	Gas	[49]
	Dengying Fm	Z_2	Weiyuan	Restricted sea plateau	Algae-rich dolostone and dolostone	Sapropel	0.1%−0.5%	Post mature	Gas	[56−58]

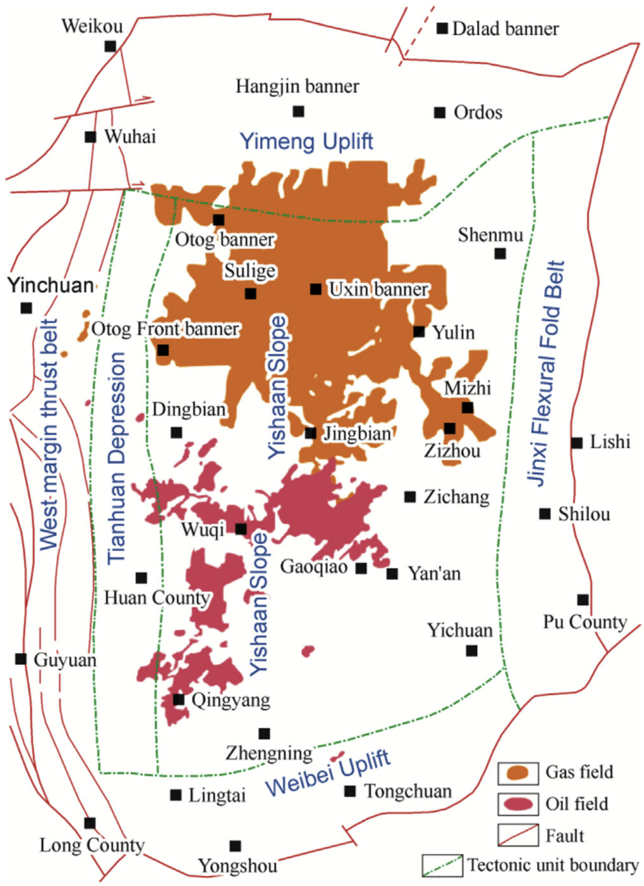

Fig. 17. Distribution of oil and gas fields in the Ordos Basin [59].

the Bohai Bay Basin, natural gas was generated in residual deep Cenozoic basins and crude oil in shallow Paleogene basins, which also exhibits the pattern of upper oil and lower gas.

2.1. The Songliao Basin

In the Songliao Basin, Paleozoic metamorphic rocks, i.e. Lower Paleozoic hypometamorphic rocks and Upper Paleozoic epimetamorphic rocks constitute the principal part of the basement. There is still dispute over whether or not there are pre-Cambrian crystalline massifs. The basin experienced three evolutionary stages of fault subsidence, depression and tectonic inversion in the Late Mesozoic, with their tectonic frameworks quite different from the first to the other two stages (Figs. 13 and 14). As a part of Northeast China sub-rift group, Upper Jurassic to Lower Cretaceous fault depression group in the deeper section consists of four NN fault depression zones filled with Shahezi, Huoshiling and Yingcheng volcanic rocks, coal measures and limnetic mudstone. The Upper Cretaceous depression from the Greater Khingan Mountains in the west to Sanjiang region in the east covered an area much bigger than the current extension. The lower fault depression group controlled by regional rifting may be active rifts over super giant mantle bulge; the upper depression was formed by regional thermal decay. The Songliao Basin experienced multiphase tectonic inversions during fault subsidence and depression, the intensity of which decreases from east to west [37], causing strong reworking of the southeast part of the basin.

Source rocks of different type developed respectively in the fault subsidence and depression stages in the basin. Limnetic-lacustrine source rocks deposited in the fault subsidence stage distribute in each fault depression [35,38]. The major source rocks are Shahezi limnetic mudstone with *TOC* of over 1.0%. The coal seams have *TOC* of 29% on average, and organic matters mainly of humic type and some sapropel and hybrid types [28]. The diversity of organic matters demonstrates the complexity of sedimentary environments and parent materials [39]. The Songliao basin has thermal gradient of 3.8 °C/100 m and 4.2 °C/100 m in petroliferous regions on average at present [40], which were even higher in the geologic history. Source rocks of the fault subsidence stage buried between 3000 and 5000 m have reached a highly-mature to post-mature stage, i.e. gas-generating window. For example, the deep formations in Xujiaweizi and Qian'an fault depressions, where hundred billion cubic meters of natural gas have been discovered.

The Songliao Basin was a giant depression with a large lake area and water depth at the depression stage. During this stage, a set of source rocks, medium-deep lacustrine mudstone, deposited, which is of superior quality due to the effects of transgression and deep hydrothermal fluids in the lithosphere. The organic matter is mainly sapropelic kerogen with very high abundance, some source beds are even organic matter layers covering an area of tens of thousands of kilometers. Due to the thermal effect of deep mantle plume, most source rocks have subjected to intense heat and entered an oil-generating window.

The petroleum exploration in the basin started in 1955 and Daqing oil field was discovered in the depression zone in

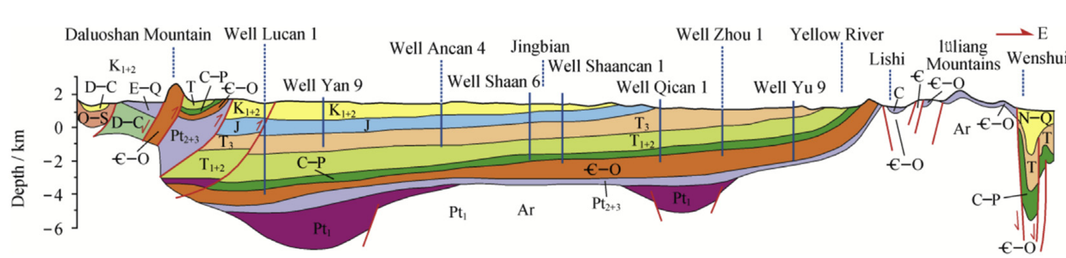

Fig. 18. Geologic section across the Ordos Basin [60].

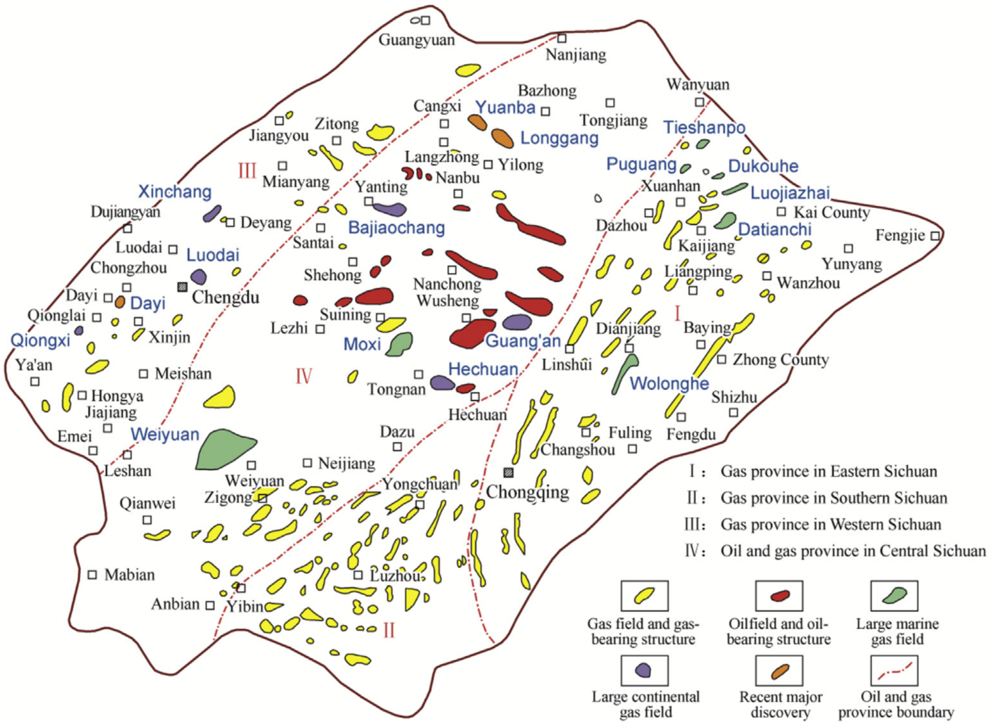

Fig. 19. Distribution of oil and gas fields in the Sichuan Basin [61].

1959. Xushen gas field was discovered in the deep fault depression after 2000. Up to now a number of oil and gas fields have been discovered in the basin; in the upper section there are large oil fields such as Daqing and in the lower section there are large gas fields such as Xushen.

2.2. The Bohai Bay Basin

The Bohai Bay Basin is a large superimposed basin (Figs. 15 and 16) on the Archeozoic-Early Proterozoic crystalline basement. The basin has experienced 1.8 billion years of formation, reconstruction and superimposition. Basin prototypes include the Middle and Late Proterozoic Yanliao Aulacogen, the Cambrian-Ordovician Great North China marine carbonate craton, the Carboniferous−Permian Great North China transitional clastic craton, small-scale Jurassic-Cretaceous fault depression group on regional uplift, and the Paleogene-Quaternary rift basin. Each prototype basin now within the current Bohai Bay Basin is composed of various residual basins reconstructed to varying degrees due to the later tectonic process during superimposition. For example, the Yanliao Aulacogen mainly occurred in the northeast margin of the North China Craton and was reworked differentially at a later stage; intra-continental orogenic process took place where tectonic reworking was the strongest. The prototype of the Cambrian-Ordovician basin was a part of the Early Paleozoic North China Craton, which was uplifted and denuded for two hundred million years in the Silurian, Devonian and Early Carboniferous and was broken into pieces by rifting and differential subsidence in the Indosinian, Yanshanian and Himalayan. The prototype of the Carboniferous−Permian craton basin was also broken and severely denuded by rifting and differential subsidence in the Indosinian, Yanshanian and Himalayan. The Jurassic-Cretaceous fault depressions were generally small depressions on uplifts. The Paleogene fault depression group was generated under mantle plume swelling background, with its fault depressions different in scale distributed orderly in the space. The Cenozoic basin is the dominant one among the above prototype basins and residual Carboniferous−Permian craton basin is the most important part of pre-Cenozoic residual basins.

Similar to other superimposed basins, there are two sets of hydrocarbon kitchens, one in the upper section and the other in the lower section, in the Bohai Bay Basin under the co-control of source and heat.

There developed Lower Paleozoic marine source rocks and Carboniferous−Permian transitional source rocks [31−35], which, deeply buried and subjected to intense heat process, mainly generate natural gas. For example, source rocks in the Qianmiqiao gas field in the Huanghua Depression are Ordovician marine post-mature mudstone, which has also been drilled in the Bozhong Sag in the Bohai Bay Basin. Source rocks in the Suqiao gas field in the Jizhong Depression and Wenliu gas field in the Dongpu Sag, the Linqing Depression are mainly Carboniferous−Permian coal measures of high maturity.

Medium-deep and deep lacustrine source rocks of the Paleogene Kongdian Fm, 4th, 3rd, 1st and 2nd member of the Shahejie Fm and Lower Dongying Fm deposited in the Cenozoic Erathem in the Bohai Bay Basin [29,30]. The basin is a typical hydrothermal one due to the thermal effect of deep

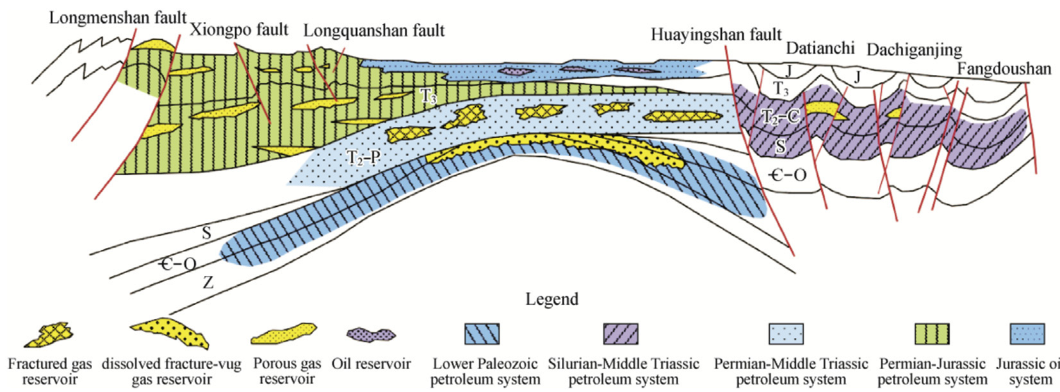

Fig. 20. Geologic section showing petroleum systems in the Sichuan Basin [62].

mantle plume, where most source rocks, mature or low-mature in local areas, mainly generated oil.

The extensive petroleum exploration in the basin started in the 1950s, followed by a bloom of onshore oil field discoveries, e.g. Shengli oil field, Dagang oil field, Huabei oil field, Liaohe oil field, Zhongyuan oil field, etc. from the 1960s to the 1980s, and some large offshore oil fields have been discovered in the Bohai Sea area since the 1980s. Up to now hundreds of oil fields and some medium-sized and small gas fields have been discovered in the basin. Petroleum reserves have cumulated to over ten billion tons and gas reserves amount to 2000×10^8 m^3, with dissolved gas as the main type. Oil and natural gas were generated separately in Cenozoic and Paleozoic source rocks; oil resources are very large and gas resources are relatively small.

3. Double hydrocarbon generation mode of “upper oil and lower gas” in central China under the co-control of source and heat

In central China, there are the Ordos Basin, the Sichuan Basin, and other basins (Fig. 1) on fossil craton basements. These basins are residual superimposed basins with multi-sets of source rocks evolved from different prototypes after multiphase tectonic movements and various tectonic reworking (Table 4). Source rocks have experienced different thermal effects due to the impacts of regional heat flow field and burial history, giving birth to a pattern of upper oil and lower gas, i.e. gas is generated mainly in lower series of strata and oil mainly in upper series of strata.

3.1. The Ordos Basin

The Ordos Basin lying on Archean to Early Proterozoic crystalline basement was mainly formed in the Middle and Late Proterozoic, Early Paleozoic, Late Paleozoic and Mesozoic. The prototypes at various stages differ greatly and were not limited within the current basin. The current basin is the superimposition of the remains of each prototype basin (Figs. 17 and 18). In accordance with geologic period, the prototypes of Middle and Late Proterozoic basins were Jin, Ji and Shan aulacogens; geographically, the aulacogens in NE direction lie in the west part of the North China Craton, and the evolution of the Ordos aulacogen is related to the Qinglin-Qilian-Kunlun Ocean. The prototype of Early Paleozoic marine craton, Late Paleozoic transitional craton and the contemporaneous Bohai Bay Basin is one of the different parts of the same basin, i.e. the North China Craton. Only marginal Ordos Basin in the west was reworked by the Himalayan cycle in the Paleozoic. The internal part of the craton mainly experienced overall sustained subsidence and deep burial without much fracturing and folding deformation. North Ordos is adjacent to the Yinshan Uplift; due to sustained uplifting of the Yinshan Mountains in the Carboniferous−Permian, large coal-measure deltas pushing towards the basin occurred at mountain front. An important prototype basin of Ordos came into being in the Mesozoic Era. In the Triassic Period, a large depression extending to the east of Zhengzhou in NWW strike parallel with the Qinling Mountains range occurred in the southwest margin of the North China Craton due to intense northward compression of the Qinling Mountains in the south, blocking of Inner Mongolian axis in the north, and the Bohai Bay Basin uplifting in the northeast. In the Jurassic Period, an inland depression was shaped owing to the eastward pushing of the Liupan Mountain and the Helan Mountains, the uplifting of the Lüliang Mountains, the blocking of the Yinshan Mountains in the north and orogenic movement at the Qinling Mountains in the south. The Cretaceous prototype depression in north-south strike was limited within west basin margin and the east margin of the Helan Mountains. The Cenozoic Ordos Basin was surrounded by fault depressions, i.e. the Hetao fault depression group in the northwest and the Fenwei graben group in the southeast; the main part of the basin shrank and died out. The current Ordos Basin is superimposed by several residual prototype basins. The area experienced uplifting and denudation for two hundred million years between the Early and the Late Paleozoic, cutting and denudation at the end of the Triassic, generation of the Lüliang Uplift in the east basin margin due to the Yenshan movement, and occurrence of the Hetao and Fenwei graben system and separation of the Ordos Basin with the plateau land form due to the block faulting from the Himalayan movement.

Table 5
Sandwich type hydrocarbon generation mode in west China petroleum provinces.

Basin	Source rock								Thermal maturity	Product	References
	Major source bed	Age	Region	Sedimentary facies	Lithology	Kerogen	Mudstone *TOC*	Mudstone S_1+S_2/ (mg g^{-1})	R_o		
Junggar	Anjihaihe Fm	E	West of south basin margin	Semi-deep lacustrine	Dark mudstone	Sapropel to sapropel hybrid	1.1%	1.0–4.0	Low mature	Oil	[63]
	Toutunhe Fm Xishanyao Fm San'gonghe Fm Badaowan Fm	$J_{1\text{-}2}$	Changji-Shihezi Depression	Limnetic	Dark mudstone, coals and carbargilite	Humic hybrid to humic	0.5%–2.2%	0.4–99.7	0.5%–1.0% Some highly mature	Gas	[64–66]
	Baijiantan Fm Karamay Fm Baikouquan Fm	T	Distributing extensively	Shore lake and shallow lacustrine to semi-deep lacustrine	Dark mudstone	Humic, some humic hybrid	0.2%–3.1%/1.4%	0.2–8.9/2.	0.7%–0.8%/ 0.72%	Oil	[67]
	Lucaogou Fm Hongyanchi Fm	P_2	South basin margin	Deep to semi-deep lacustrine	Dark mudstone and oil shale	Sapropel hybrid	0.6%–10.0%/4.4%	0.1–67.2/19.7	0.7%–0.9%/0.8%	Oil	[64,65]
	Lower Batamayi'neishan Fm	C_2	Distributing extensively	Shallow to semi-deep marine	Dark mudstone with some coals and carbargilite	Humic hybrid to humic	0.1%–5.5%/2.3%	0.1–15.6/2.	Mature to highly mature	Gas	[68,69]
	Dishuiquan Fm Shiqiantan Fm	$C_{1\text{-}2}$	Distributing extensively	Littoral-coastal-transitional	Dark mudstone with some coals and carbargilite	Mainly sapropel hybrid	0.2%–3.6%/1.0%	0.1–1.8/0.	1.7%–2.3%	Gas	[68,69]
Tarim		E	Southwest Depression	Lacustrine						Oil	
	Yangye Fm Kangsu Fm	$T\text{-}J_{1\text{-}2}$	Kashgar Banner	Limnetic	Mudstone and carbargilite	Hybrid and humic	0.3%–11.9%/ (0.86%–2.96%)		1.6%–2.0%	Gas	[70,71]
	Balikelike Fm Kunkelaqi Fm	P_1	Southwest Depression	Transitional	Carbonate rock and mudstone	Sapropel and hybrid, some humic	Mudstone: 0.2% –0.5% Carbonate rock: 0.3% –0.5%	1.8	>2.0%	Gas	[72]
	Bachu Fm Xiaohaizi Fm Karashayi Fm	$C_{1\text{-}2}$	South Bachu Salient	Platform margin to platform slope	Bioclastic limestone	Hybrid and humic	Mudstone: 0.3% –2.0% Carbonate rock: 0.1% –0.9%		0.7%–0.9% Deep depression: 1.4%–2.6%	Gas	[72,73]
	Salgan Fm Yin'gan Fm	$O_{2\text{-}3}$	North slope in Central Tarim and south slope in North Tarim	Semi-enclosed to enclosed estuarine	Marl	Hybrid and humic	0.1%–5.4%/0.8%	Central Tarim: 0.1 –4.7	0.9%–1.3%	Oil	[72,74–77]
	Yu'ertus Fm	$€_{1-2}$	$€_1$Kalpin and Mandong area $€_{1-2}$: Bachu and Central Tarim	$€_1$: continental shelf $€_{1-2}$: restricted platform	$€_1$: argillutite $€_{1-2}$: carbonate rock	Sapropel	Argillutite: ?-5.5%/ 1.8% Carbonate rock: ?-2.2%/0.9%	?-0.9/0. Carbonate rock: ?-0.11/0.1	East and Southwest Tarim: 1.8%–3.6% Bachu: 1.7% –2.1%	Gas	[72,74–77]
Qaidam	Qigequan Fm	Q_{1+2}	Sanhu area in the middle and east	Lacustrine and limnetic	Dark mudstone and carbargilite	Humic and hybrid	0.2%–0.5%/0.3%		0.2%–0.5%	Gas	[78–80]
	Ganchaigou Fm	$E_3^{1+2}–N_1$	West basin	Brackish lacustrine	Dark mudstone	Hybrid	0.1%–2.4%	1.58–4.58	Low mature to mature	Oil	[81–83]
	1st and 7th members of Dameigou Fm	$J_{1\text{-}2}$	Mesozoic depression at north margin	Limnetic and coal-bearing	Dark shale, mudstone, oil shale and coals	Humic hybrid and humic	1st Member: 0.9%–3.8%/2.2%	1st Member: 0.3–11.3/3.	Highly mature to post mature	Gas	[84]
	Hurleg Fm	C_2	East basin	Littoral, lagoon and	Black argillutite,	Sapropel, hybrid	Mudstone: 0.4%	Mudstone: 0.4–6.1/	0.7%-1.4/1.1%	Gas	[85]

(*continued on next page*)

Table 5 (*continued*)

Basin	Source rock								Thermal maturity	Product	References
	Major source bed	Age	Region	Sedimentary facies	Lithology	Kerogen	Mudstone *TOC*	Mudstone $S_1 + S_2$/ (mg g^{-1})	R_o		
	Jabsar Gaxun Fm			swamp	carbonaceous shale and coals	and humic	−3.3%/1.4% Limestone: 0.05% −1.3%/0.3%	2.2 Limestone: 0.5−0.8/ 0.5	Dulan area: post mature		

In the Ordos Basin, there are three sets of source rocks, Middle and Late Proterozoic to the Early Paleozoic marine source rocks, Late Paleozoic transitional coal-measure source rocks [43−46] and Late Triassic medium-deep lacustrine source rocks [43−45]. The two major source rocks in the Paleozoic, the deeply buried Ordovician and Carboniferous−Permian source rocks, experienced intense thermal effect generated natural gas. Upper Triassic source rocks of medium-deep lacustrine mudstone mainly generated oil.

Middle Ordovician (the Pingliang Fm) source rocks, composed of deep-water slope dark mudstone deposits, mainly spread over the west margin and Pingliang-Long County-Baoji in the south margin of the Ordos Basin. The source rock bed is 20−50 km in the west margin and 10−15 km in the south margin. The dark mudstone is 80−100 m on average and up to 200 m thick; the marl is about 60 m thick and its thickens increases gradually from north to south. The *TOC* generally ranges from 0.5 to 1.0% and reach 2.17% at most. Except for some areas in the west margin, source rocks have generally evolved into a highly-mature to post-mature stage [44,47]. Extensive Carboniferous−Permian coal-measure source rocks are deposited in the barrier-type coastal tide flat-lagoon bog mucks and tide-dominate deltaic bog muck at an early stage and in meandering river flood plains to shallow deltaic plains at a later stage. The Late Paleozoic coal reaches 40 m thick at maximum, and the dark mudstone is 40−500 m thick in total. Parent materials are humic kerogen. The *TOC* of coal and mudstone is 70%−85% and 2%−3% respectively. Gas fields mainly distribute in the area with the R_o of 1.2%−2.4%, and hydrocarbon generation center is the area with gas-generating intensity of more than 20×10^8 m^3/km^2, which accounts for 55.2 percent of the total basin at present [44,46].

Upper Triassic Yanchang Fm Deep lacustrine source rocks turn up in the south of the basin, in which there are some sections very rich in organic matter. The *TOC* ranges from 0.22% to 36.75% and organic matter is mainly composed of sapropel-hybrid kerogens. The R_o value is 0.43%−1.15% [43,44], denoting low mature to mature stage due to the effect of heat, and the source rocks are generating oil on the whole.

Since the first well drilled in 1907, hundreds of oil and gas fields, discovered in upper formations and lower formations respectively, have been discovered in the Ordos Basin. The oil reserves reached billions of tons and gas reserves reached trillions of cubic meters. The source and heat works jointly to give birth to the pattern of “lower gas and upper oil” in the Ordos Basin, with huge gas resources generated in lower formations and huge oil resources generated in upper formations.

3.2. The Sichuan Basin

The Sichuan Basin residing on the Late Proterozoic crystalline basement was also superimposed by multi-stage residual basins of Sinian to Quaternary overburdens (Figs. 19 and 20). The prototype basin changed from the aulacogen group on the Yangtze Craton in the Sinian Period to a residual craton in the Paleozoic-Middle Triassic. Late Triassic

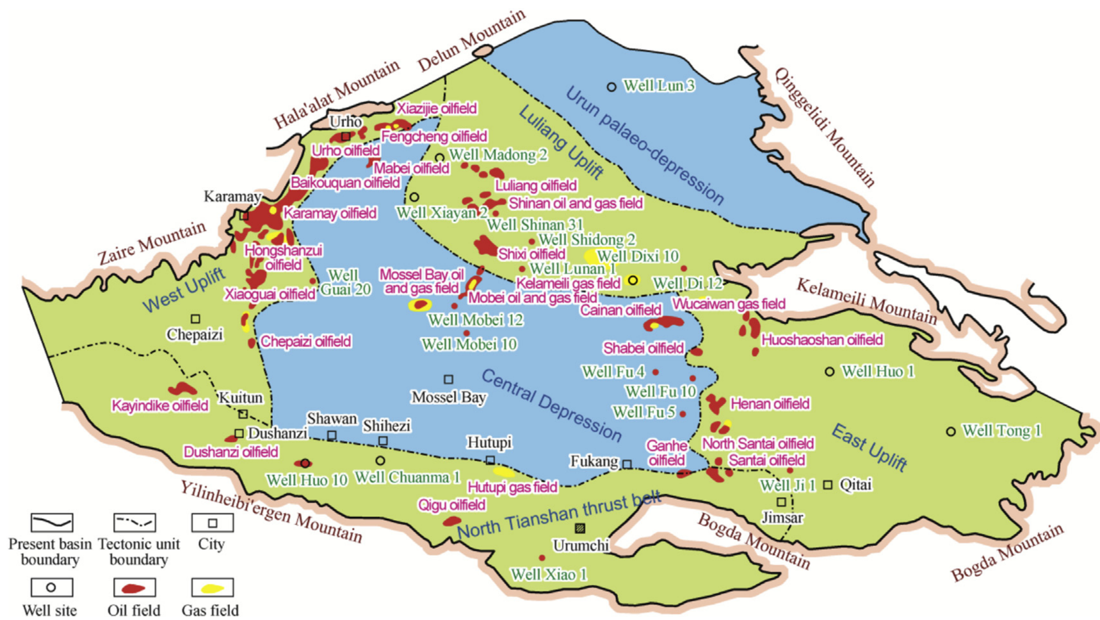

Fig. 21. Distribution of oil and gas fields in the Junggar Basin [64].

prototype was a composite foreland-craton basin, in the west and north margin of which were foredeep sags resulted from the Longmen Mountain orogenic belt in the west and South Qinling orogenic belt in the north moving towards the basin, which transited into a craton in the southeast. The basin has changed into a continental depression basin from the Jurassic. In the Yanshanian, the Middle and Lower Yangtze Platforms experienced intense compression and uplifting due to the activities of near-Pacific structural domain, resulting in orogeny within the craton and the formation of the shape of Sichuan Basin. Since the Neogene Period, the Upper Yantze Platform has been squeezed from all directions, with the island of Taiwan having been suffering nappe extrusion westward, the Qinghai-Tibet Plateau having been squeezed eastward and the Qinling orogenic belt having been compounded. Therefore, the Sichuan basin has been uplifted and died out finally. There developed Sinian, Silurian, Carboniferous–Permian, Triassic and Jurassic source rocks in the Sichuan Basin [48–58].

In the Sichuan Basin, Sinian and Silurian marine sapropelic source rocks and Carboniferous-Permian-Triassic transitional coal-measure and marine source rocks are deeply buried with high thermal evolution degree and mainly generate natural gas [49–58]. In addition, Middle Permian and underlying marine source rocks in the southwest of the basin experienced extremely high heat flow (higher than 70 mW/m^2) and uplifting and denudation due to the impacts of Emeishan mantle plume in the Middle Permian; after that the source rocks haven't subjected to further deep burial or high heat flow; in other words, the Upper and Lower Paleozoic source rocks reached the highest palaeo-geotemperature or maturity

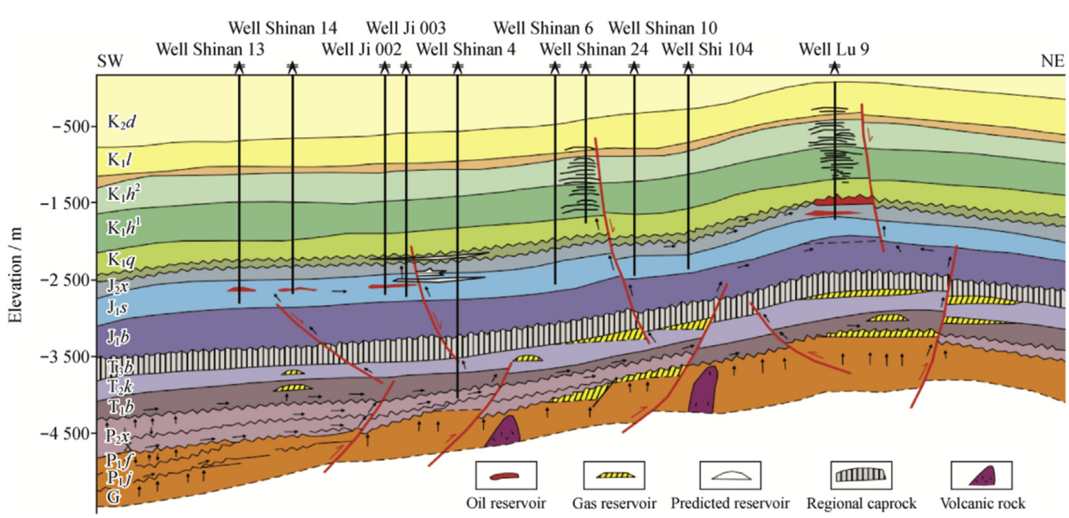

Fig. 22. Geologic section showing hydrocarbon accumulation patterns in the Junggar Basin [69].

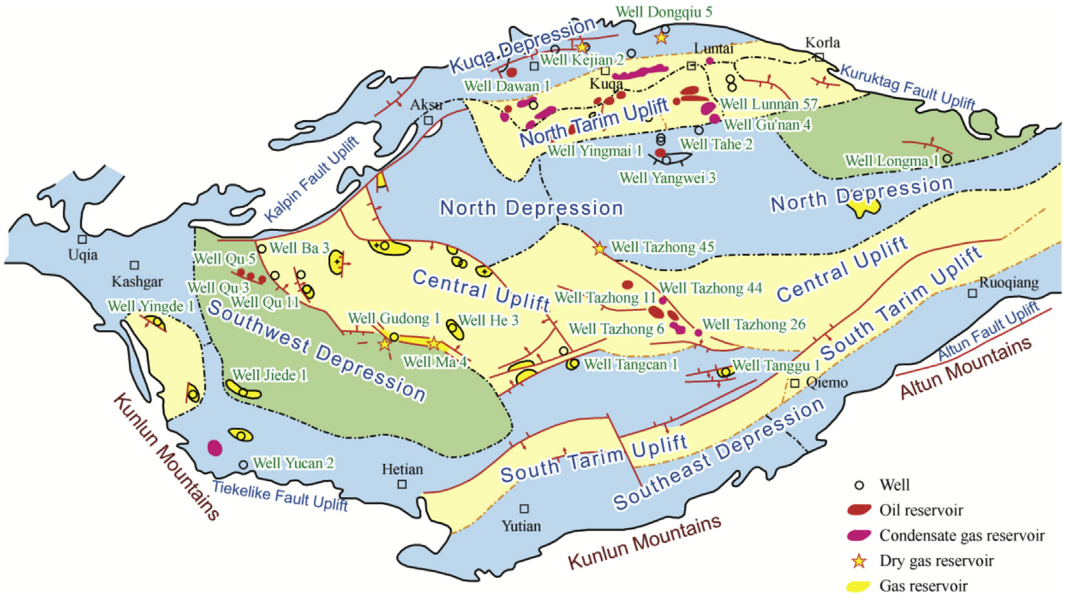

Fig. 23. Distribution of oil and gas fields in the Tarim Basin [74].

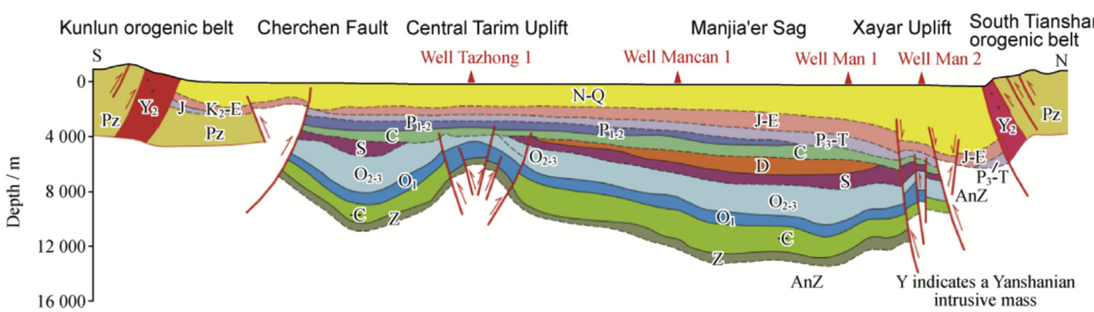

Fig. 24. Regional geologic section across the Tarim Basin [50].

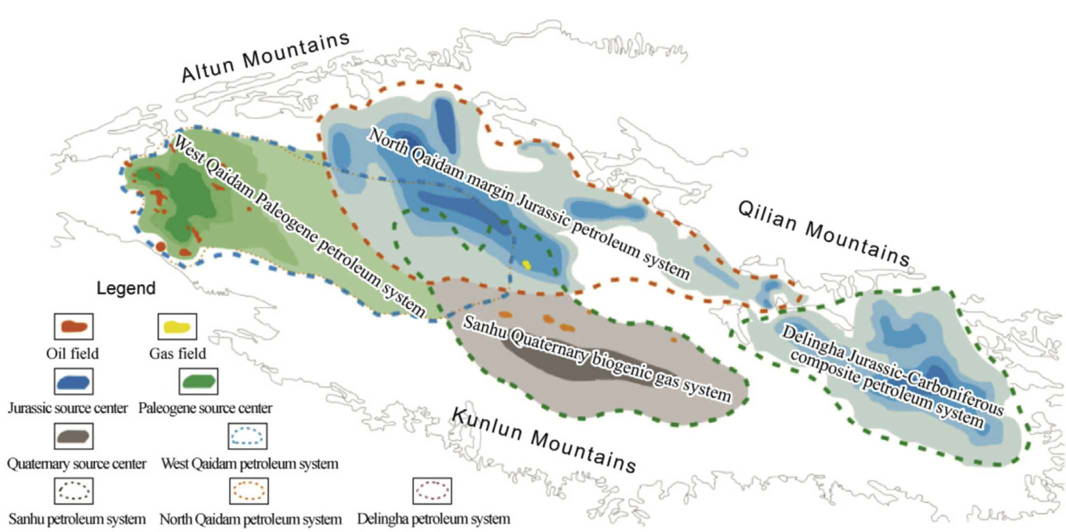

Fig. 25. Distribution of oil and gas fields in the Qaidam Basin [82].

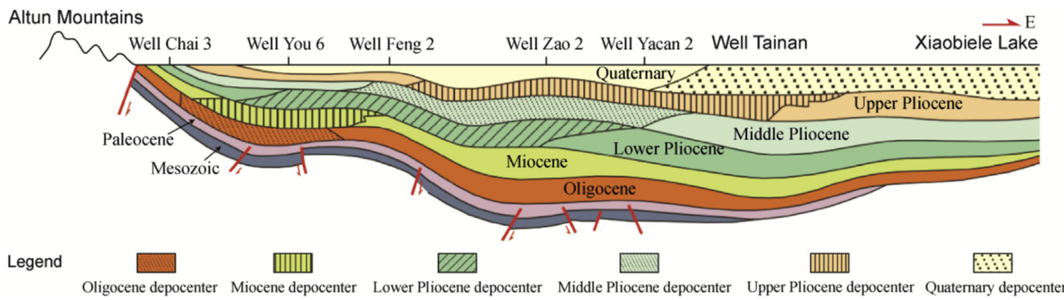

Fig. 26. Geologic section showing a depocenter migration in the Qaidam Basin [88].

in Middle Permian with a R_o of 2.1%–3.8%, and entered into a post-mature stage, and during which a large amount of gas was generated [52,53]. Coal-measure source rocks in the first, third and fifth members of the Upper Triassic Xujiahe Fm spread over the foreland area in the whole basin. The argillaceous source rocks thicken from east to west and reach 1400 m in the depression center. The coal seams spread widely, and are generally 2–10 m thick, and may be up to 25 m thick in depression. The *TOC* of mudstone is usually 0.5–6.5%, and 2.43% on average; most samples have a *TOC* of over 1.0%. Most Xujiahe source rocks became mature enough to generate hydrocarbon, mainly natural gas, in the Jurassic Period, with a R_o of 0.6%–1.5% [49,58]. Jurassic source rocks in the Sichuan Basin are lacustrine mudstone, moderate in thermal evolution and in oil generation window [48]. Under the co-control of source and heat, the basin exhibits a hydrocarbon generation pattern of “lower gas and upper oil”, i.e. oil generation in pre-Jurassic source rocks and gas generation in Upper Jurassic source rocks.

Petroleum exploration in the Sichuan Basin has a long history of thousands of years, and it is the only basin with gas development on a large scale in ancient China. Modern exploration started in the 1930s, followed by massive oil and gas discoveries since the 1950s. Up to now hundreds of gas fields have been discovered with gas reserves of up to trillions of cubic meters. Oil fields have mainly been discovered in the Jurassic System with oil reserves of less than 1×10^8 t; but the potential is quite huge and may be comparable with Yanchang Fm in the Ordos Basin [48].

4. Sandwich-type hydrocarbon generation mode in west China under the co-control of source and heat

The orogenic belts and basins in west China extend in nearly EW or NWW direction and include the basin group in north Xinjiang (the Junggar Basin, the Tuha Basin, the Santanghu Basin, etc.), the Tianshan intermontane basin group (the Yili Basin, the Yanqi Basin, etc.), the Tarim Basin, the Kunlun-Altun intermontane basin, the Qaidam Basin, the Qiangtang Basin, etc. from north to south (Fig. 1). These basins lying on the craton basement or in folded region experienced multiphase tectonic movements and have multiple sets of source rocks. The source rocks have experienced different thermal effects due to the impacts of regional heat flow field and burial history, presenting a sandwich type hydrocarbon generation mode. Different in evolution history, those basins in different regions have different hydrocarbon generation assemblages (Table 5).

4.1. Four-layer type hydrocarbon-generating assemblage in the Junggar Basin

The Junggar Basin, a sedimentary basin developed from the Kazakhstan Plate (Figs. 21 and 22), resides on the pre-Carboniferous basement. The basin experienced multiphase movement and reworking from the Carboniferous Period to the Quaternary Period. The Carboniferous prototype is inferred to be a residual ocean basin between the Paleozoic Altai orogenic belt and the Tianshan orogenic belt. The Permian prototype was a composite basin composed of a number of aulacogens with the Mahu Aulacogen in the west and the Bogda Aulacogen in the southeast. At the end of the Permian Period, surrounding orogenic belts were reactivated, giving birth to the foredeep basin. The Mesozoic prototype was a depression basin. In the Cenozoic Era the Changji-Shihezi piedmont depression came into being as a result of intense movement of the TianShan Mountain. In summary, the Junggar Basin is a composite–superimposed basin after a complicated evolutionary process.

The basin has several sets of source rocks, i.e. Carboniferous residual ocean basin marine source rocks, Permian lacustrine source rocks, Jurassic coal-measure source rocks and Paleogene lacustrine source rocks [63–69]. Mainly occurring in the Wucaiwan Sag, subjected to strong heat, and thus high in maturity, Carboniferous source rocks mainly generate natural gas, and are the only source for the Kelameili gas field [68,69]. Permian source rocks distribute in the central depression and east uplift in the basin, including the Mahu and Lu'nan Depressions in the northwest margin and the Wutongwozi Depression in east Junggar. This set of source rocks has a residual *TOC*, chloroform bitumen “A” content, total hydrocarbon content and $S_1 + S_2$ value of 1.26%, 0.1493%, 0.0820% and 0.73 mg/g on average respectively. The organic matters are mainly composed of sapropelic and hybrid kerogens, with R_o value of 0.85%–1.16%, and the source rocks are in mature to highly-mature stage, high in quality and primarily generate oil [64,65]. Early and Middle Jurassic coal-measure and limnetic source rocks developed pervasively in the basin have a big variation in organic matter abundance, and organic types are mainly sapropel hybrid and humic hybrid kerogens. These source rocks are deeply buried only in the Changji-Shihezi Depression in the south basin margin and are cooked enough to generate natural gas and light oil [64,66]. Paleogene lacustrine source rocks are limited in the southwest basin margin and only those buried in the southwest have been subjected to strong heat and are matured enough to generate oil [63].

Before the establishment of PRC, only the Dushanzi oil field was discovered in the Junggar Basin. Now dozens of oil and gas fields have been discovered, which show a four-layer type oil and gas generation mode, i.e. gas generation in the Carboniferous and Jurassic Systems and oil generation in the Permian and Paleogene Systems.

4.2. Four-layer type hydrocarbon-generating assemblage in the Tarim Basin

The crystalline basement of the Tarim Plate formed in the Tarim movement eight hundred million years ago. After three tectonic cycles, which are Sinian−Devonian cycle (regional extension in the Early Sinian-Early Ordovician and regional compression in the Middle and Late Ordovician-Devonian), Carboniferous−Permian cycle (regional subsidence in the Carboniferous Period and regional extensional fault subsidence in the Permian Period), and Mesozoic and Cenozoic cycle (regional foredeep occurrence in the Triassic-Paleogene and inland squeezing subsidence in the Neogene-Quaternary), a typical multi-cycle superimposed basin formed eventually. In each tectonic cycle, there were depressions of different properties splicing laterally, and tectonic reworking occurred inside a cycle or between two cycles, therefore, the present basin is the superimposition of the residual basins of different prototypes (Figs. 23 and 24).

Lower and Middle Cambrian formations distribute in the Manjia'er Sag, the Awati Sag, etc. The thickness of basin-lagoon argillutite in the Lower Cambrian Yu'ertus Fm is less than 200 m; the *TOC* of intra-platform sag and evaporitic lagoon source rocks varies from 0.50% to 21.96% and that of basin and continental shelf source rocks from 0.5% to 5.0% [74−77]. Middle and Lower Ordovician Heitu'ao Fm source rocks cover a smaller area than the Lower and Middle Cambrian deep continental shelf-basin source rocks; the thickness of continental shelf-basin shale is less than 200 m and the *TOC* varies from 0.01% to 7.62%. Shale of deep continental shelf facies in the Middle and Upper Ordovician Salgan Fm occurs in the Awat and Tangguzibasi Sags with a thickness of less than 50 m. In the Awat Sag, the source rocks are buried deep in the west and shallow in the east; the maximum buried depth exceeds 10000 m in the west, and that near Well Manxi 2 in the east is about 6500 m. The source rocks in the Tangguzibasi Sag are buried at a depth of around 5000 m. In Aman transition zone between Central Tarim and North Tarim, the source rocks in the intra-platform sag are less than 150 m thick. In the basin facies region in East Tarim (the Queerueke Fm), the thickness of dark mudstone source rocks is less than 150 m. In Middle and Upper Ordovician Salgan Fm, shales of basin-continental shelf facies and of intra-platform sag facies are usually less than 150 m thick and 0.01%−12.82% in *TOC* [74−77].

There are three sets of limnetic coal-measure source rocks in Kuqa Depression, Tarim basin, namely, the Late Triassic Tariqike Fm, the Early Jurassic Yangxia Fm and the Middle Jurassic Kizilnur Fm. In the three pan-swamp stages, their sedimentary environment transited frequently from shallow lake to swamped-shallow lake and finally to swamp. Three short transgressions happened during this period [71,72,86]. In the Kuqa Depression, Jurassic coal beds reach up to 50 m thick and mudstone is 500−1000 m thick. Triassic coal beds are up to tens of meters thick and the total source-rock thickness reaches 800 m. The kerogen is mainly of humic type. The coal beds have *TOC* of 55−70%, and $S_1 + S_2$ of 20−70 mg/g, and a maximum of 100 mg/g. The carbargilite has *TOC* of more than 8% and $S_1 + S_2$ value of more than 35 mg/g. The mudstone has *TOC* of 1%−4% and $S_1 + S_2$ value of 1−6 mg/g. The source rocks in gas generation window have R_o value of 0.83%−2.00%, those in gas generation peak have R_o value of 0.8%−1.6%. Gas-generating intensity exceeds 20×10^8 m^3/km^2 in the main part of the Kuqa Depression and ranges $(60-80) \times 10^8$ m^3/km^2 in the depocenter [71,72,86].

In the platform area (the Manjia'er Sag, the Awati Sag, etc.), Cambrian source rocks, deeply buried and high in thermal evolution degree, mainly generate natural gas and condensate oil. Ordovician marine source rocks are not very high in thermal maturity owing to the low thermal gradient in spite of their great burial depths, so they mainly generate oil and condensate oil. Triassic-Middle and Lower Jurassic coal-measure source rocks deeply buried in foredeep depressions have experienced strong heat effect and mainly generate natural gas. Distributing in the southwest of the basin, Cenozoic lacustrine source rocks are not very high in thermal evolution degree due to their small burial depths and low thermal gradients there, thus they mainly generate oil.

In summary, the Tarim Basin has a hydrocarbon generation pattern of “bottom gas (in the Cambrian System), lower oil (in the Ordovician System), middle gas (in the Triassic and Jurassic Systems) and upper oil (in the Cenozoic Erathem)”. The Cambrian and Ordovician source rocks mainly distribute in Manjia'er sag. Due to different heat effects, Cambrian source rocks generate gas and Ordovician source rocks generate oil. Triassic and Lower and Middle Jurassic coal measures buried in foredeep zones such as Kuqa are major source rocks in the Mesozoic continental superimposed basin; in spite of their low thermal gradients, these source rocks have experienced strong heat effect owing to their large burial depths, so they mainly generate natural gas. Lying in Kunlun foreland, the Cenozoic basin mainly produces natural gas.

4.3. Three-layer type hydrocarbon-generating assemblages in the Qaidam Basin

The Qaidam Basin is held between the Altun, Qilian and Kunlun orogenic belts (Fig. 25) on the basement of pre-Sinian crystalline rock series and Paleozoic folded system [81,82,87]. This massif experienced multi-phase basin generation and reworking in the Mesozoic Era and Cenozoic Era due to the impacts of plate collisions south of the Kunlun orogenic belt. In the Triassic Period, the Qiangtang terrane was spliced with the Eurasia continent along Lungma Tso-Yushu suture zone and collision orogens occurred pervasively in the Middle Kunlun arc belt; Triassic deposits were generally missing except in regions as Xiangride Farm in east Qaidam. So the basin mainly formed after the Indosinian movement and roughly experienced Jurassic-Cretaceous fault subsidence, Paleogene-Neogene fault subsidence and Quaternary depression. Jurassic-Cretaceous fault depressions distribute largely in the north of the basin, which was a depression regionally with a local fault depression. Paleogene-Neogene fault depression was located in the west of the basin, and Quaternary depression was in the east of the basin. Depocenters of fault depressions (and depressions) migrated from north (in the Jurassic) to west (in the Tertiary) and finally to southeast (in the Quaternary), which reflects the co-control of the Altun, Kunlun and Qilian orogenic belts (Fig. 26).

The major source rocks in the Qaidam Basin include Middle and Lower Jurassic source rocks, Paleogene lacustrine source rocks and Quaternary limnetic source rocks [78–85]. Among them, Middle and Lower Jurassic source rocks are mainly dark mudstone with an area of 1×10^4 km^2, in which the kerogen is mainly of humic and sapropel-humic types and the *TOC* is generally 1.65%–8.26%, and 3.00% on average. These source rocks have a chloroform bitumen "A" content of 1000–2000 mg/L and total hydrocarbon content of 1158 mg/L, R_o value of 2.0% in general, indicating that they are at a highly-mature stage [84]. The Paleogene lacustrine source rocks spread over an area of 1×10^4 km^2, containing kerogen of mostly humic-sapropel and sapropel-humic types. With *TOC* of 0.23%–1.54%, and 0.88% on average, chloroform bitumen "A" content of 400–1200 mg/L, R_o value of 0.5%–1.0%, indicating that these source rocks have entered a mature stage [81–83]. Quaternary limnetic source rocks with an area of 2×10^4 km^2, contain kerogen of humic and sapropel-humic types. This set of source rocks has *TOC* of 0.15%–0.46%, and 0.30% on average, and chloroform bitumen "A" content of generally 100–200 mg/L. The source rocks have the R_o value of 0.22%–0.47%, indicating that they are at an immature stage [78–80].

The Qaidam Basin has a sandwich–type hydrocarbon generation mode, i.e. lower gas generation in Early and Middle Jurassic coal-measure and limnetic source rocks in the north basin margin, middle oil generation in Oligocene, Miocene and Pliocene lacustrine source rocks, and upper gas generation in Quaternary organic-rich limnetic source rocks.

5. Conclusions

In spite of a complicated generation process, oil and gas distribute in some patterns controlled by key factors. The formation of an oil and gas field includes hydrocarbon generation, migration and accumulation; hydrocarbon generation is the paramount condition, and oil and gas fields usually occur in or close to a source rock series. Hydrocarbon would accumulate within or above or below source rock series where natural fractures are underdeveloped, which is known as intra-source or proximal accumulations. If an area is rich in fractures, oil and gas would distribute around the source center radially in distal, proximal and intra-source reservoirs. Some typical scenarios of intra-source or proximal accumulations include lower gas generation (in the Paleozoic) and upper oil generation (in the Upper Triassic) in the Ordos Basin with lower gas fields (in the Paleozoic) and upper oil fields (in the Upper Triassic and Jurassic); the Sichuan Basin have the same characteristics. In the Songliao Basin in the east, natural gas was generated in Early Cretaceous fault depressions and therefore has accumulated in the Lower Cretaceous formations and crude oil was mainly generated in Late Cretaceous depressions and therefore has accumulated in the Upper Cretaceous formations. Quaternary hydrocarbon generation and accumulation in the Qaidam Basin has the same case. Some provinces have distal, proximal and intra-source hydrocarbon accumulations. For example, oil and gas in the southeast sea area in China were mainly generated in the Paleogene System and have accumulated in the Neogene and Paleogene Systems; some of them have accumulated in the pre-Tertiary formations. Oil in the Bohai Bay Basin was mainly generated in Paleogene fault depressions and has accumulated in Archean-Neogene formations close to Paleogene fault depressions. In the Junggar Basin in the west, hydrocarbon has been generated, migrated and accumulated in several series of strata, which is controlled by source kitchens in lateral direction. In summary, oil and gas field distribution depends on the distribution of source rock series.

Previous researches mainly focused on the effects of a single factor, e.g. structures, depositions, source rocks, etc. to probe into the hydrocarbon generation in a basin, which is very important to but not sufficient for petroleum exploration. Some basins with similar tectonic types may vary greatly in hydrocarbon generation. For example, the Bohai Bay Basin and the Southern North China Basin are both Paleogene-Neogene extensional basins, but more than ten billion tons of oil has been discovered in the former, while even a small oil field has not yet been found in the latter. The same is true of the two basins with similar sedimentary features. For example, Jurassic coal-measure strata dominate both the Yili Basin and the Tuha Basin, but no reservoirs has been found yet in the former, and hundreds of millions of tons of oil and gas reserves have been discovered in the latter. The hydrocarbon type can not be attributed to the type of source rocks simply. For example, Oligocene Enping coal-measure source rocks in the Zhujiangkou Basin generate a small amount of oil in the Zhu I Depression, natural gas in the Zhu II Depression, and both oil and gas in the Zhu III Depression.

It is believed that for a hydrocarbon accumulation to occur, structures and depositions are indirect controlling factors, while source rocks and heat are the very direct factors, the coupling of which decides whether the source kitchen can form, and the type (oil, gas, or oil and gas) and the scale of the kitchen if the kitchen does exist. For superimposed basins, various prototype basins have different source rocks, which, experiencing different heat effects, form different hydrocarbon distribution patterns. It would be of great significance to understand these hydrocarbon generation patterns in oil and gas exploration.

There is a near-shore oil belt and a far-shore gas belt extending thousands of kilometers in the southeast sea area in China. Petroleum exploration has been conducted extensively in the near-shore regions since the 1970s, resulting in the discovery of Bohai, east Zhujiangkou, west Zhujiangkou and Beibu Bay oil accumulation zones in the near-shore belt and Xihu, Baiyun, Yacheng and Yinggehai gas accumulation zones in the far-shore belt. But the far-shore belt is still low in exploration degree and is a potential area for finding new natural gas reserves.

Onshore basins such as Songliao, Bohai Bay, Ordos and Sichuan in east and central China all exhibit the hydrocarbon generation pattern of "upper oil and lower gas". Shallow oil has been highly explored in general, but deep gas not fully explored would be the focus in future exploration, especially in ancient craton basins such as Sichuan and Ordos with multiple sets of deep source rocks.

The Junggar, Tarim and Qaidam Basins in west China have multiple sets of source beds and the recent exploration activities have demonstrated extensive prospects both in lateral and vertical directions. The discovery of Kelameili gas field which was formed in a Carboniferous residual ocean basin shows that the basin basement may also have great exploration potential. Conventional oil plays are greatly extended to deep zones due to the discovery of oil at a buried depth of 8000 m in the Tarim Basin. Three large oil fields discovered in the west of the northwest margin of the Junggar Basin have demonstrated large hydrocarbon generation potential in Permian hydrocarbon-rich sag in Mahu. The discovery of the giant Wutongwozi tight oil reservoir in the east of the basin has opened up a new prospect of unconventional oil and gas exploration.

There still have some new prospects in the above four oil and gas provinces in addition to those discussed in the paper. Far-shore deep water zones in China's sea area have considerable oil and gas potential. Peripheral basins of Songliao in northeast rift region in the east province, the Proterozoic and Paleozoic in the Southern North China Basin, Qinling intermontane basins and Mesozoic and Cenozoic fault depressions in southeast upwelling areas all have oil and gas potential. The Weihe Basin and deep Chuxiong Basin in the central province have gas potential. The Gansu Corridor, Altai intermontane basins, Tianshan intermontane basins, Kunlun-Qilian-Qinling intermontane basins and the Qiangtang Basin also have oil potential. There must be oil and gas resources in the above basins as long as there are appropriate source rocks and heat conditions.

In summary, hydrocarbon generation assemblages in China increase from a single hydrocarbon generation assemblage in southeast sea area to double hydrocarbon generation assemblages in east and central China and finally to sandwich-type hydrocarbon generation assemblages in west China. Regions with substantial oil generation include the near-shore belt in southeast sea area, the upper series of strata in the east and central provinces and the Ordovician, Permian and Paleogene in the west province. Regions with substantial gas generation include the far-shore belt in southeast sea area, the medium-deep zones in the east and central provinces and the Cambrian, Carboniferous, Jurassic and Quaternary in the west province. Generally speaking, there are a variety of oil and gas fields distribution patterns: gas fields below oil fields, oil fields below gas fields, gas fields outside oil fields, and oil fields outside gas fields. In conclusion, China's oil and gas exploration areas remain vast.

Fund project

National Basic Research Program of China (973 Program) "Fundamental research on petroleum resources generation and distribution in deep basins in the South China Sea" (No.2009CB219400) and National Science and Technology Major Project "Key technologies of deep sea petroleum exploration" (No.2008ZX05025, 2011ZX05025).

References

[1] Zhang Gongcheng. Co-control of source and heat: the generation and distribution of hydrocarbons controlled by source rocks and heat. Acta Pet Sin 2012;33(5):723–38.
[2] Zhang Gongcheng, Zhu Weilin, Mi Lijun, Zhang Houhe, Liang Jianshe, Qu Hongjun. Regular distribution of inside-oil fields and outside-gas fields controlled by source rocks and heat in China offshore basins. Acta Sedimentol Sin 2010;28(5):987–1005.
[3] Li Youchuan, Deng Yunhua, Zhang Gongcheng. Zoned distribution of source rocks and hydrocarbon offshore China. China Offshore Oil Gas 2012;24(1):6–12.
[4] Sun Guihua, Gao Hongfang, Peng Xuechao, Wu Jiaoqi. Geologic and tectonic characteristics of the Mekong Basin, South Vietnam. Mar Geology Quat Geology 2010;30(6):25–33.
[5] Yao Yongjian, Wu Nengyou, Xia Bin, Wan Rongsheng. Petroleum geology of the Zengmu Basin in the southern South China Sea. Geology China 2008;35(3):503–13.
[6] Petroleum Management Unit of Petronas Research and Scientific Services. The petroleum geology and resources of Malaysia. Kuala Lumpur: Petronas; 1999. p. 499–542.
[7] Todd SP, Dunn ME, Barwise AJG. Characterizing petroleum charge systems in the tertiary of S.E. Asia. In: Fraser AJ, Matthews SJ, Murphy RW, editors. Petroleum geology of Southeast Asia, vol. 126. Geological Society Special Publication; 1997. p. 25–47.
[8] Tan DNK, Lamy JM. Tectonic evolution of the NW Sabah continental margin since the Late Eocene. Bull Geological Soc Malays 1990;27:241–60.
[9] Ma Liangtao, Wang Chunxiu, Niu Jiayu, Zheng Qiugen, Lei Baohua. Hydrocarbon geology in NW Sabah Basin and controlling factors on hydrocarbon accumulation. Mar Geol Front 2012;28(7):36–43.
[10] Tong Zhigang, Zhao Zhigang, Yang Shuchun, Chen Chunfeng. Research on thermal evolution and hydrocarbon expulsion history of source rocks in low-exploration basins: a case study on Jiaojiang Sag, East China Sea Basin. Petroleum Geology Exp 2012;34(3). 319–324,329.
[11] Huang Baojia. Gas potential and its favorable exploration areas in Qiongdongnan Basin. Nat Gas Ind 1999;19(1):34–8.
[12] Huang Baojia, Xiao Xianming, Dong Weiliang. Characteristics of hydrocarbon source rocks and generation &evolution model of natural gas in Yinggehai Basin. Nat Gas Ind 2002;22(1):26–30.
[13] Jin Qinghuan, Liu Zhenhu, Chen Qiang. The central depression of the Wan'an Basin, South China sea: a giant abundant hydrocarbon-generating depression. Earth Sci J China Univ Geosciences 2004;29(5):525–30.

[14] Zhang Gongcheng, Chen Guojun, Zhang Houhe, Li Youchuan, Liang Jianshe, Yang Shuchun. Regular distribution of inside-oil fields and outside-gas fields controlled by source rocks and heat in China offshore basins. Acta Sedimentol Sin 2012;30(1):1−19.
[15] Mi Lijun, Yuan Yusong, Zhang Gongcheng, Hu Shengbiao, He Lijuan, Yang Shuchun. Characteristics and genesis of geothermal field in deep-water area of the Northern South China Sea. Acta Pet Sin 2009;30(1):27−32.
[16] Qiu Zhongjian, Gong Zaisheng. Oil and gas exploration in China: part IV. Beijing: Geological Publishing House; 1999. p. 942.
[17] Li Chunrong, Zhang Gongcheng, Liang Jianshe, Zhao Zhigang, Xu Jianyong. Characteristics of fault structure and its control on hydrocarbons in the Beibuwan Basin. Acta Pet Sin 2012;33(2):195−203.
[18] Zhang Gongcheng, Miao Shunde, Chen Ying, Zhao Zhigang, Li Youchuan, Zhang Houhe, et al. Distribution of gas enrichment regions controlled by source rocks and geothermal heat in China Offshore Basins. Nat Gas Ind 2013;33(4):1−17.
[19] Tong Zhigang, He Qing, He Shibin, Yang Shuchun, Xiong Binhui, Hao Jianrong. Geothermal field and its effect on source rock in the Xihu Sag, East China Sea Basin. Petroleum Geology Exp 2009;31(5). 466−471,484.
[20] Zhang Gongcheng, Mi Lijun, Wu Shiguo, Tao Weixiang, He Shibin, Lǚ Jianjun. Deepwater area-the new prospecting targets of northern continental margin of South China Sea. Acta Pet Sin 2007;28(2):15−21.
[21] Xie Yuhong, Tong Chuanxin. Conditions and gas pooling modes of natural gas accumulation in the Yacheng 13-1 Gas Field. Nat Gas Ind 2011;31(8). 1−5,127.
[22] Xie Yuhong, Zhang Yingchao, Li Xushen, Zhu Jiancheng, Tong Chuanxin, Zhong Zehong, et al. Main controlling factors and formation models of natural gas reservoirs with high-temperature and overpressure in Yinggehai Basin. Acta Pet Sin 2012;33(4):601−9.
[23] Liu Baoming, Jin Qinghuan. Hydrocarbon geological conditions and distribution characteristics of Zengmu Basin in southern South China Sea. Trop Ocean 1997;16(4):18−25.
[24] Zhang Gongcheng, Xie Xiaojun, Wang Wanyin, Liu Shixiang, Wang Yibo, Dong Wei, et al. Tectonic types of petroliferous basins and its exploration potential in the South China Sea. Acta Pet Sin 2013;34(4):611−27.
[25] Ge Shasha. Hydrocarbon source rock evaluation of Nenjiang formation, Songliao Basin. Inn Mong Petrochem Ind 2013;(15):129−30.
[26] Feng Zihui, Fang Wei, Li Zhenguang, Wang Xue, Huo Qiuli, Huang Qiuyan, et al. Depositional environment of terrestrial petroleum source rocks and geochemical indicators in the Songliao Basin. Sci China: Earth Sci 2011;41(9):1253−67.
[27] Zan Ling, Zhang Zhihuan, Huang Junping, He Xin, Feng Jinru, Wu Yuyuan, et al. Geochemical characteristics of natural gas and its origin in Changling Fault Depression of Songliao Basin, northeastern China. Nat Gas Geosci 2010;21(2):331−7.
[28] Luo Xia, Sun Fenjin, Shao Mingli, Wang Zhihong, Zeng Fuying, Zhao Zehui, et al. Geochemistry of deep coal-type gas and gas source rocks in Songliao Basin. Petroleum Explor Dev 2009;36(3):339−46.
[29] Zhu Weilin, Mi Lijun, Gong Zaisheng. Hydrocarbon accumulation and exploration in Bohai Sea area. Beijing: Science Press; 2009.
[30] Liu Qing, Zhang Linye, Song Guoqi, Wang Ru. Sedimentary organic facies of the Paleogene Upper $E_{2\text{-}3}s_4$ source rocks in Jiyang Depression. Geological J China Univ 2011;17(4):586−93.
[31] Zhang Min, Wang Dongliang, Zhu Cuishan, Zhao Wenjing. Study on quantitative identification model of mixed oils from Suqiao-Wen'an area in Jizhong Depression, part I: genetic types and geochemical characteristics of crude oils. Nat Gas Geosci 2004;15(2):115−9.
[32] Zhao Xianzheng, Jin Qiang, Zhang Liang, Liang Hongbin, Jin Fengming. Accumulation conditions and perspectives of coal-derived hydrocarbon of Carboniferous-Permian in northern Jizhong Depression, Bohai Bay Basin. Petroleum Geology Exp 2010;32(5):459−64.
[33] Zhang Qingfeng, Pan Zhongliang, Luo Xiaoping, Chang Zhenheng. Oil source correlation and oil charge history of Shahejie Formation in Wendong Area. J Southwest Petroleum Univ Nat Sci Ed 2010;32(2):31−4.
[34] Zhu Yanming, Wang Xiaohui, Zhang Cong, Yuan Wei, Cai Chao, Chen Shangbin. Hydrocarbon-generation evolution of the Permo-Carboniferous coal measure in Dongpu Depression. Acta Pet Sin 2007;28(6):27−31.
[35] Dai Jinxing. Potential areas for coal-formed gas exploration in China. Petroleum Explor Dev 2007;34(6). 641−645,663.
[36] Feng Zhiqiang, Zhang Shun, Feng Zihui. Discovery of enveloping surface of oil and gas overpressure migration in the Songliao Basin and its bearing on hydrocarbon migration and accumulation mechanisms. Sci China Earth Sci 2011;41(12):1872−83.
[37] Zhang Gongcheng, Xu Hong, Liu Hefu, Zhu Defeng. Inversion structures in relation at oil and gas field distribution in Songliao Basin. Acta Pet Sin 1996;17(2):9−14.
[38] Zhao Wenzhi, Zou Caineng, Feng Zhiqiang, Hu Suyun, Zhang Yan, Li Ming, et al. Geological features and evaluation techniques of deep-seated volcanic gas reservoirs, Songliao Basin. Petroleum Explor Dev 2008;35(2):129−42.
[39] Ren Yanguang, Zhu Defeng, Wan Chuanbiao, Feng Zihui, Li Jingkun, Wang Cheng. Geological characteristics of deep layers in northern part of Songliao Basin and orientation for natural gas exploration. China Pet Explor 2004;9(4):12−8.
[40] Lu Shuangfang, Li Jiaona, Liu Shaojun, Feng Zihui, Li Jingkun, Huo Qiuli, et al. Oil generation threshold depth of Songliao Basin: revision and its significance. Petroleum Explor Dev 2009;36(2):166−73.
[41] Li Desheng. Tectonics of polycyclic superimposed oil and gas basins in China. Beijing: Science Press; 2012.
[42] Han Zongyuan, Miao Jianyu, Bu Zhanqi. The comparative study on organic geochemical characters of the mesozoic source rocks in T_3y and J_2y of Zhenyuan in Ordos Basin. Geoscience 2007;21(3):532−7.
[43] Deng Nantao, Zhang Zhihuan, Bao Zhidong, Wang Fubin, Liang Quansheng, Li Wenhao, et al. Geochemical features and identification marks for efficient source rocks of Yanchang Formation in southern Ordos Basin. J China Univ Petroleum Nat Sci Ed 2013;37(2):135−45.
[44] Zhang Wenzheng, Li Jianfeng. Study on oil-gas sources in Ordos Basin. China Pet Explor 2001;6(4):28−36.
[45] Liu Xinshe, Xi Shengli, Fu Jinhua, Wang Tao, Wang Xin. Natural gas generation in the upper paleozoic in Ordos Basin. Nat Gas Ind 2000;20(6):19−23.
[46] Wang Guicheng, Shi Dongfeng, Bai Jianlin, Gao Yuequan. Evaluation for hydrocarbon source rocks in Paleozoic Yichuan of Ordos Basin. J Yan'an Univ Nat Sci Ed 2012;31(3):84−8.
[47] Li Yanjun, Chen Yicai, Yang Yuancong, Lǚ Qiang, Zhang Jun, Shi Xiaoying. Source rock evaluation and characteristics of hydrocarbon generation from lower paleozoic carbonate in Ordos Basin. Oil Gas Geology 1999;20(4):349−53.
[48] Liang Digang, Ran Longhui, Dai Danshen, He Zixin, Ouyang Jian, Liao Qunshan, et al. A recognition of the prospecting potential of Jurassic large-area and non-conventional oils in the central-northern Sichuan Basin. Acta Pet Sin 2011;32(1):8−17.
[49] Zhu Guangyou, Zhang Shuichang, Liang Yingbo, Ma Yongsheng, Dai Jinxing, Li Jian, et al. The characteristics of natural gas in Sichuan Basin and its sources. Earth Sci Front 2006;13(2):234−48.
[50] Wei Guoqi, Liu Delai, Zhang Lin, Yang Wei, Jin Hui, Wu Shixiang, et al. The exploration region and natural gas accumulation in Sichuan Basin. Nat Gas Geosci 2005;16(4):437−42.
[51] Zou Chunyan, Zheng Ping, Yan Yuxia, Wang Qingwei, Zhang Min. Characteristics of source rock in lower Triassic Feixianguan formation, Sichuan Basin. Nat Gas Explor Dev 2009;32(1):8−12.
[52] Liu Quanyou, Jin Zhijun, Gao Bo, Zhang Dianwei, Xu Mei'e. Types and hydrocarbon generation potential of the Permian source rocks in the Sichuan Basin. Oil Gas Geology 2012;33(1):10−8.
[53] Teng Ge'er, Qin Jianzhong, Fu Xiaodong, Yang Yunfeng, Xie Xiaomin. Hydrocarbon source rocks evaluation of the Upper Permian Wujiaping formation in northeastern Sichuan area. J Palaeogeogr 2010;12(3):334−45.
[54] Zhang Xiaolong, Li Yanfang, Lǚ Haigang, Yan Jianping, Tuo Jincai, Zhang Tongwei. Relationship between organic matter characteristics and

depositional environment in the Silurian Longmaxi formation in Sichuan Basin. J China Coal Soc 2013;38(5):851−6.
[55] Wang Shejiao, Wang Lansheng, Huang Jinliang, Li Xinjing, Li Denghua. Accumulation conditions of shale gas reservoirs in Silurian of the Upper Yangtze region. Nat Gas Ind 2009;29(5):45−50.
[56] Wei Guoqi, Shen Ping, Yang Wei, Zhang Jian, Jiao Guihao, Xie Wuren, et al. Formation conditions and exploration prospects of Sinian large gas fields, Sichuan Basin. Petroleum Explor Dev 2013;40(2):129−38.
[57] Chen Zongqing. Gas exploration in Sinian Dengying formation, Sichuan Basin. China Pet Explor 2010;15(4):1−14.
[58] Huang Jizhong, Chen Shengji, Song Jiarong, Wang Lansheng, Gou Xuemin, Wang Tingdong, et al. Hydrocarbon source system and the formation of large-medium gas field in Sichuan Basin. Sci Sin Ser D 1996;26(6):504−10.
[59] Qiu Zhongjian, Deng Songtao. New thinking of oil-gas exploration in China. Acta Pet Sin 2012;33(S1):1−5.
[60] Jia Chengzao, Li Benliang, Zhang Xingyang, Li Chuanxin. The formation and evolution of marine basins in China. Chin Sci Bull 2007;52(S1):1−8.
[61] Ma Yongsheng, Cai Xunyu, Zhao Peirong, Luo Yi, Zhang Xuefeng. Distribution and further exploration of the large-medium sized gas fields in Sichuan Basin. Acta Pet Sin 2010;31(3):347−54.
[62] He Dengfa, Li Desheng, Tong Xiaoguang, Zhao Wenzhi. Accumulation and distribution of oil and gas controlled by paleo-uplift in poly-history superimposed basin. Acta Pet Sin 2008;29(4):475−88.
[63] Guo Chunqing, Shen Zhongmin, Zhang Linye, Xu Xingyou, Kong Xiangxin, Zhu Rifang. Biogenic origin characteristics of hydrocarbon source rocks and classification of oils in the south part of Junggar Basin, China. J Chengdu Univ Technol Sci Technol Ed 2005;32(3):257−62.
[64] He Dengfa, Chen Xinfa, Zhang Yijie, Kuang Jun, Shi Xin, Zhang Liping, et al. Enrichment characteristics of oil and gas in Junggar Basin. Acta Pet Sin 2004;25(3):1−10.
[65] Bin Yang. Source rock evaluation in Junggar Basin. Xinjiang Pet Geol 1982;3(2):20−38.
[66] Fu Guoyou, Song Yan, Zhao Mengjun, Qin Shengfei, Da Jiang. Analysis of the controlling effects of source rocks on middle-large sized gas field formation. Nat Gas Geosci 2007;18(1):62−6.
[67] Chen Jianping, Liang Digang, Wang Xulong, Deng Chunping, Jin Tao, Xiang Shuzheng, et al. The discovery and significance of the crude oils derived from triassic source rocks in the Junggar Basin. Geochimica 2003;32(6):582−90.
[68] Guo Jianying, Li Zhiming. Study of gas source and characteristics of carboniferous hydrocarbon source rock in the Junggar Basin. Petroleum Geology Exp 2009;31(3):275−81.
[69] He Dengfa, Chen Xinfa, Kuang Jun, Yuan Hang, Wu Xiaozhi, Du Peng, et al. Characteristics and exploration potential of carboniferous hydrocarbon plays in Junggar Basin. Acta Pet Sin 2010;31(1):1−11.
[70] Li Guoyu, Lü Minggang, Zhao Xianzheng. Atlas of petroliferous basins in China. Beijing: Petroleum Industry Press; 2002. p. 437−42.
[71] Jia Chengzao. Structural characteristics and oil/gas accumulative regularity in Tarim Basin. Xinjiang Pet Geol 1999;20(3):177−83.
[72] Jia Chengzao, Zhou Xinyuan, Wang Zhaoming, Pi Xuejun, Li Qimin. Discovery of Kela-2 gas field and exploration technology. China Pet Explor 2002;7(1):79−88.
[73] Zhao Mengjun, Zhang Shuichang, Zeng Qiang, Zhang Baomin, Qin Shengfei, Li Mei, et al. Bachu carbonate rocks of carboniferous source rocks and crude oil characteristics in Tarim Basin. Mar Orig Pet Geol 2000;5(S1):23−8.
[74] Pang Xiongqi, Zhou Xinyuan, Jiang Zhenxue, Wang Zhaoming, Li Sumei, Tian Jun, et al. Hydrocarbon reservoirs formation, evolution and distribution in the superimposed basin, Western China. Acta Geol Sin 2012;86(1):1−103.
[75] Liang Digang, Zhang Shuichang, Zhang Baomin, Wang Feiyu. Understanding on marine oil generation in China based on Tarim Basin. Earth Sci Front 2000;7(4):534−47.
[76] Ma Anlai, Zhang Shuichang, Zhang Dajiang, Jin Zhijun. Oil and source correlation in Lunnan and Tahe heavy oil fields. Oil Gas Geology 2004;25(1):31−8.
[77] Kang Yuzhu. Cases of discovery and exploration of marine fields in China (part 4): Tahe Oil field in Tarim Basin. Mar Orig Pet Geol 2005;10(4):31−8.
[78] Wei Guoqi, Liu Delai, Zhang Ying, Li Benliang, Hu Guoyi, Li Jian. Formation mechanism, distribution feature and exploration prospect of the quaternary biogenic gas in Qaidam Basin, NW China. Petroleum Explor Dev 2005;32(4):84−9.
[79] Gu Shusong, Zhou Zhuhong. Geochemical characteristics and classification of natural gas in quaternary in the east part of Qaidam Basin. Nat Gas Ind 1993;13(2):1−6.
[80] Gu Shusong. Formation of gas reservoirs in quaternary at the east part of Qaidam Basin and their exploration prospects. Nat Gas Ind 1990;10(1):1−6.
[81] Fu Suotang, Zhang Daowei, Xue Jianqin, Zhang Xiaobao. Exploration potential and geological conditions of tight oil in the Qaidam Basin. Acta Sedimentol Sin 2013;31(4):672−82.
[82] Yuan Jianying, Fu Suotang, Cao Zhenglin, Yan Cunfeng, Zhang Shuichang, Ma Dade. Multi-source hydrocarbon generation and accumulation of plateau multiple petroleum system in Qaidam Basin. Lithol Reserv 2011;23(3):7−14.
[83] Zhang Mingfeng, Tuo Jincai, Zhang Xiaojun, Wu Chenjun, Chen Ru, Guo Lijun. Geochemical characteristics of the source rocks from Wunan-Lücaotan area in Qaidam Basin. Nat Gas Geosci 2012;23(4):636−45.
[84] Zhai Zhiwei, Zhang Yongshu, Yang Hongmei, Sha Wei, Nian Xiuqing, Hao Xiaomei, et al. Characteristics of effective source rocks in the jurassic and hydrocarbon accumulation patterns in the areas near the northern margin of the Qaidam Basin. Nat Gas Ind 2013;33(9):36−42.
[85] Duan Hongliang, Zhong Jianhua, Wang Zhikun, Ma Feng, Yin Chengming, Wen Zhifeng. Evaluation of carboniferous hydrocarbon source rocks in the eastern Qaidam Basin, China. Geological Bull China 2006;25(9):1135−42.
[86] Zhao Mengjun, Zhang Shuichang. Genetic classification of natural gas and conditions of gas reservoir formation in Tarim Basin. China Pet Explor 2001;6(2):27−31.
[87] Zhai Guangming, Xu Fengyin. A reconsideration of Qaidam Basin for a great breakthrough in oil and natural gas exploration. Acta Pet Sin 1997;18(2):4−10.
[88] Gu Shusong, Xu Wang. Discussion on the article of application of fault control hydrocarbon theory to realize a great breakthrough of petroleum exploration in Qaidam Basin. Acta Pet Sin 2003;24(6):107−12.