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Preface

With the development of hydrocarbon exploration, it is difficult to make a major breakthrough in the middle-shallow strata. As a result, the hydrocarbon exploration in deep strata is a great significance to increase reserves and stabilize productvity in the hydrocarbon fields. In recent years, the deep hydrocarbon exploration has become a global trend, and the discovery of high-temperature ultra-deep hydrocarbon reservoirs challenges the traditional understanding of hydrocarbon geology. It is a great academic significance and economic value to carry out the deep hydrocarbon geological research.

This book provides theoretical directions and technical supports for the breakthrough of deep hydrocarbon exploration and the increase in the reserves of scale by systematically analyzing and summarizing the formation conditions, distribution rules and main controlling factors of deep hydrocarbon fields, and predicting the exploration prospect of deep hydrocarbon onshore in China based on the exploration research and latest progress of deep hydrocarbon in key petroliferous basins onshore such as Sichuan Basin, Tarim Basin and Ordos Basin in recent years. This book focuses on the analysis and discussion of the hydrocarbon generation mechanism in deep source rocks, the rules of hydrocarbon accumulation in ancient strata during the tectonic period, the hydrocarbon accumulation potential in gypsum-carbonite symbiosis and subsalt strata, the main controlling factors and distribution rules of deep hydrocarbon fields, and the significant superseding layers in deep strata. The geological understandings of the formation and distribution of deep large hydrocarbon fields are preliminarily obtained, that is, full hydrocarbon supplied by two types of source kitchens, large-scale reservoirs formed by three types of rocks, hydrocarbon accumulation controlled by three types of ancient source rocks and hydrocarbon accumulation crossing major tectonic stages.

This book is divided into five chapters: Chap. 1 is written by Hu Suyun, Wang Tongshan, Xu Zhaohui, Zhao Xia, etc.; Chap. 2 is written by Wang Tongshan, Li Yongxin, Qin Shengfei, Chen Yanyan, Ma Kui, Fang Jie, etc.; Chap. 3 is written by Liu Wei, Jiang Qingchun, Shi Shuyuan, Li Qiufen, Huang Qingyu, Wang Kun, Zhao Zhenyu, He Youbin, Zhang Yueqiao, Zhai Xiufen, Bai Bin, etc.; Chap. 4 is written by Wang Tongshan, Liu Wei, Jiang Hua, Bo Dongmei, He Dengfa, etc.; and Chap. 5 is written by Wang Zecheng, Xu An Na, Jiang Qingchun, Gu Zhidong, Shi Shuyuan, Xu Zhaohui, Lu Weihua, Li Jun, Yuan Miao, Fu Ling, Lin Tong, Sun Qisen, etc. This book is finalized by Hu Suyun and Wang Tongshan.

Academician Zhao Wenzhi, Prof. Gao Ruiqi, Prof. Gu Jiayu, Prof. Luo Ping, Prof. Zhang Baomin and other experts put forward valuable suggestions for the preparation and examination of the manuscript, and we express our heartfelt thanks here.

Because of the complexity of deep hydrocarbon exploration research and the limited level of writers, there are many inadequacies in the book, so criticism from readers are warmly expected.

Beijing, China

Suyun Hu
Tongshan Wang

About This Book

The prospect of onshore deep oil and gas exploration in China is predicted in this book by the analysis on major formation conditions of deep oil and gas reservoirs, major control factors and distribution rules of deep large oil and gas fields, based on the two major scientific issues in key onshore petroliferous basins of China, such as the hydrocarbon generation and accumulation of deep oil and gas.

This book can be used as a reference or auxiliary teaching material for many majors in colleges and universities, such as geological resources and geological engineering, resource exploration engineering, petroleum engineering and others as well as for scientific researchers and production technicians engaged in oil and gas exploration and development.

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Contents

Chapter 1
Introduction

With the increasing pressure of oil and gas supply and energy security risks, it has become an inevitable trend for oil and gas exploration to deep and ultra-deep strata. In recent years, with the improvement of technology in exploration and development, oil and gas reservoirs distributed in extreme environments such as deep sea, deep strata and polar regions have been identified as the main directions of exploration and development, and a number of large-middle oil and gas fields have been discovered in the deep strata. Compared with the middle-shallow oil and gas accumulation theory, the deep oil and gas accumulation theory is not mature enough. Therefore, in order to meet the basic status of domestic oil and gas resources supply, we must promote the development of deep oil and gas exploration through the systematic summarization and research.

1.1 Exploration and Geological Characteristics of Global Deep Hydrocarbon Fields

Despite the late beginning of exploration in deep hydrocarbon fields, the great discoveries and breakthroughs have been made in petroliferous basins all over the world, and the oil and gas production is increasing year by year. The formation conditions of deep oil and gas fields are different from those in the middle-shallow strata. In the future, with the continuous process in geological theories and the exploration and the development of technology in deep oil and gas, the deep oil and gas reserves will be substantially improved.

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1.1.1 Definition of Deep Strata

As for the definition of deep strata, there is no strict international standard and different countries and institutions have different views (Hansheng and Feng 2000; Ministry of Land and Resources 2005; Wenzhi et al. 2014; Guangya et al. 2015). Russia defines deep strata as exploration depth greater than 4,000 m, the United States and Brazil define deep strata as exploration depth greater than 4,500 m, and Total Company defines deep strata as exploration depth greater than 5,000 m. In 2005, "Regulation of Petroleum Reserves Estimation" was issued by National Commission of Mineral Reserves, which defined deep strata as a depth of 3,500–4,500 m, and ultra-deep strata as a depth of more than 4,500 m. China Drilling Project defined deep strata as a depth of 4,500–6,000 m, and ultra-deep strata as a depth of more than 6,000 m. Based on the variation of temperature and pressure and exploration practice in the eastern and western regions of China, this book defined the strata with the buried depth of 3,500–4,500 m in the eastern area as the deep strata, and over 4,500 m as ultra-deep strata; the strata with the buried depth of 4,500–6,000 m in the western area as the deep strata, and the strata with buried depth over 6,000 m as ultra-deep strata. Deep strata have both the concepts of depth and stratigraphy, "deep" and "ancient" are the basic characteristics. According to this definition, most of the important discoveries of domestic oil and gas exploration in recent years belong to the fields of deep to ultra-deep strata.

1.1.2 Distribution and Exploration of Global Deep Hydrocarbon Fields

(1) History and situation of deep oil and gas exploration

In recent years, although a number of large and middle oil and gas fields have been discovered in the world, deep oil and gas exploration can be traced back to the 1950s. In 1956, the first deep gas reservoir in the world was discovered in the middle Ordovician carbonate rocks at a depth of 4,663 m, the Carter Knox Gasfield of Anadarko Basin, USA. In 1977, with the breakthrough of drilling and completion technology in deep strata, a dolomite gas reservoir was found in Arbuckle Group of Cambrian and Ordovician strata, Mills Ranch Gasfield, at a depth of 8097 m. In 1984, an oil reservoir was discovered in Permian dolomite reservoir of Villifortuna Trecate Oilfield, Italy, at a depth of 6,400 m. Since 1980, deep oil and gas exploration has gradually expanded from land to sea, such as the discovery of gas reservoirs in limestone reservoir of Permian Khuff Formation, Fateh Gasfield, Arabian basin, at a depth of 4,500 m in 1980. At present, the global deepest oilfield is Anchor Oilfield, USA, with a depth of more than 10,000 m and the proved reserves of 44×10^8 t; the deepest gasfield in the world is Mills Ranch Field, USA, with a depth of 7,663–8,083 m and the proved reserves of 112×10^8 m^3. Important breakthroughs of deep oil and gas exploration have been made in the deep and ultra-deep water regions, such as Mexico Gulf, eastern Brazil and West Africa, as well as the Arctic region (Timan-Burchella Basin in Russia) (O'Brien and Lerche 1988; Lerche and Lowrie 1992; Aase and Walderhaug 2005; Ehrenberg et al. 2008; Ajdukiewicz et al. 2010; Guangming et al. 2012; Cao et al. 2013; Guoping and Binfeng 2014).

The global production of deep and ultra-deep oil and gas have been increased year by year. At present, the proportion of proven reserves and production of deep oil and gas is relatively small but growing faster (Fig. 1.1). In recent years, the number of oil and gas reservoirs discovered in ultra-deep strata with more than 6,000 m in the world has been increased significantly. Since 2000, 106 oil and gas fields have been

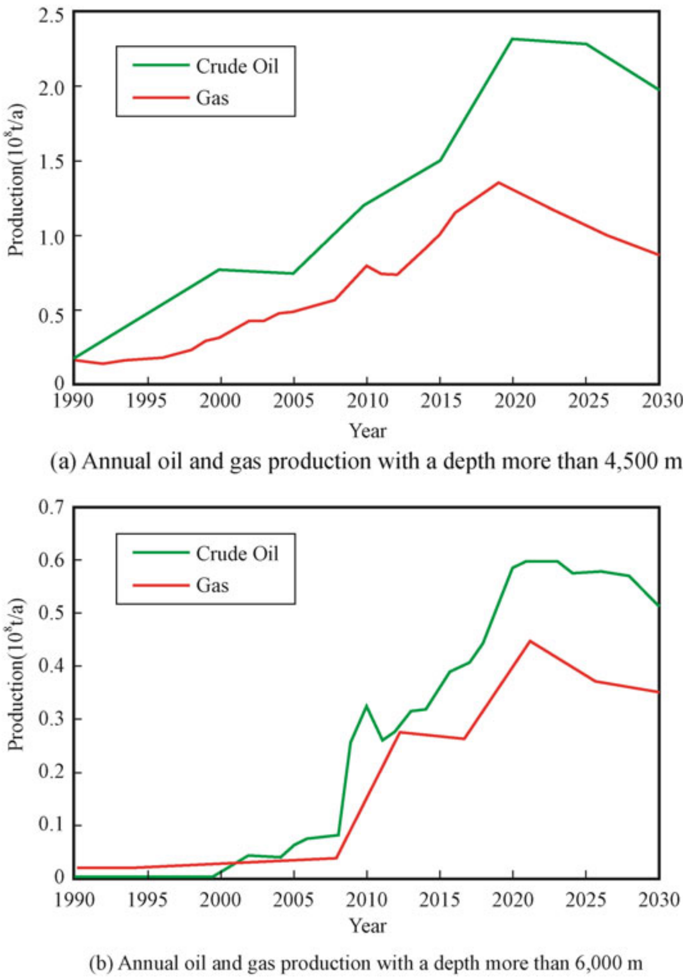

Fig. 1.1 Prediction of global deep oil and gas production (according to Xiaoguang et al. 2014)

discovered in the ultra-deep strata buried more than 6,000 m in marine area; 51 oil and gas fields have been discovered in the ultra- deep strata buried more than 6,000 m in land area. By the end of 2015, 178 industrial oil and gas fields with buried depth greater than 6,000 m have been found in the world (according to IHS). According to the preliminary results of resource evaluation, the resource extent of deep oil and gas undetected is 345 × 10^8 t with huge exploration potential. According to IHS statistics in 2013, the deep proved reserves of crude oil is 115.5 × 10^8 t and natural gas is 76 × 10^8 t (oil equivalent), accounting for 3.3% and 3.2% of the global total oil and gas reserves respectively. Among them, the ultra-deep proven oil reserves of crude oil is 15 × 10^8 t and of the natural gas is 6.2 × 10^8 t (oil equivalent), accounting for 13% and 8.2% of the total deep oil and gas reserves respectively. According to Wood Mackenzie's statistics in 2013 (Guangya et al. 2015), in 2012, the global annual production of crude oil in reservoirs deeper than 4,500 m is 1.1 × 10^8 t, accounting for 2.7% of the global total crude oil production, mainly in the Gulf of Mexico, Kazakhstan and Brazil. The oil production in the depth of more than 6,000 m is 0.26 × 10^8 t per year, accounting for 0.63% of the global total production, mainly from the Gulf of Mexico in the United States. In 2012, the global production of natural gas from reservoirs deeper than 4,500 m is 0.77 × 10^8 t (oil equivalent), accounting for 2.86% of global production, mainly from the D6 area of KG basin in India, followed by the Gulf of Mexico in the United States. The natural gas from reservoirs deeper than 6,000 m is 0.25 × 10^8 t (oil equivalent), accounting for 1% of global production, mainly from the D6 area of India and the Shah Deniz Gasfield of Azerbaijan.

(2) Distribution of deep oil and gas resources

The global deep oil and gas resources are mainly distributed in the Gulf Coast Basin, Permian Basin, Anadarko Basin, Rocky Mountain Basin, California Basin and Alaska Basin in the North America; Maracaibo Basin, Santa Cruz-Tariji Basin and Sureste Basin in the Central and South America; Dnieper-Donets Basin, Vilyuy Basin, North Caspian Basin, South Caspian Basin, Middle Caspian Basin, Amu-Darya Basin, Azov-Kuban Basin and Fergana Valley Basin in the former Soviet Union; Po Vally Basin and Aquitainethe Basin in Europe; Oman Basin in the Middle East and the Sirte Basin in Africa (Wang Yu et al. 2012).

According to the statistical data (Guangya et al. 2015), among the deep oil and gas resources discovered in the world, the proved deep oil and gas reserves in Latin America are the largest, accounting for 65% and 37% of the total deep oil and gas reserves respectively (Fig. 1.2). The proved and controlled recoverable reserves in North America are 38.28 × 10^8 t (oil equivalent), most of which are distributed in the deep and ultra-deep water areas of Mexico Gulf. The region with the largest amount of deep natural gas and condensate discovered is in the Middle East, which is about 34.20 × 10^8 t (oil equivalent), and 56% of deep natural gas is in Arabian Basin. In terms of depth and strata (Fig. 1.3), the discovered reserves decrease with depth. The deepest oil and gas fields are more than 10,000 m, and the oil and gas reserves discovered between 4,500 and 5,500 m are accounting for 80% and 84%

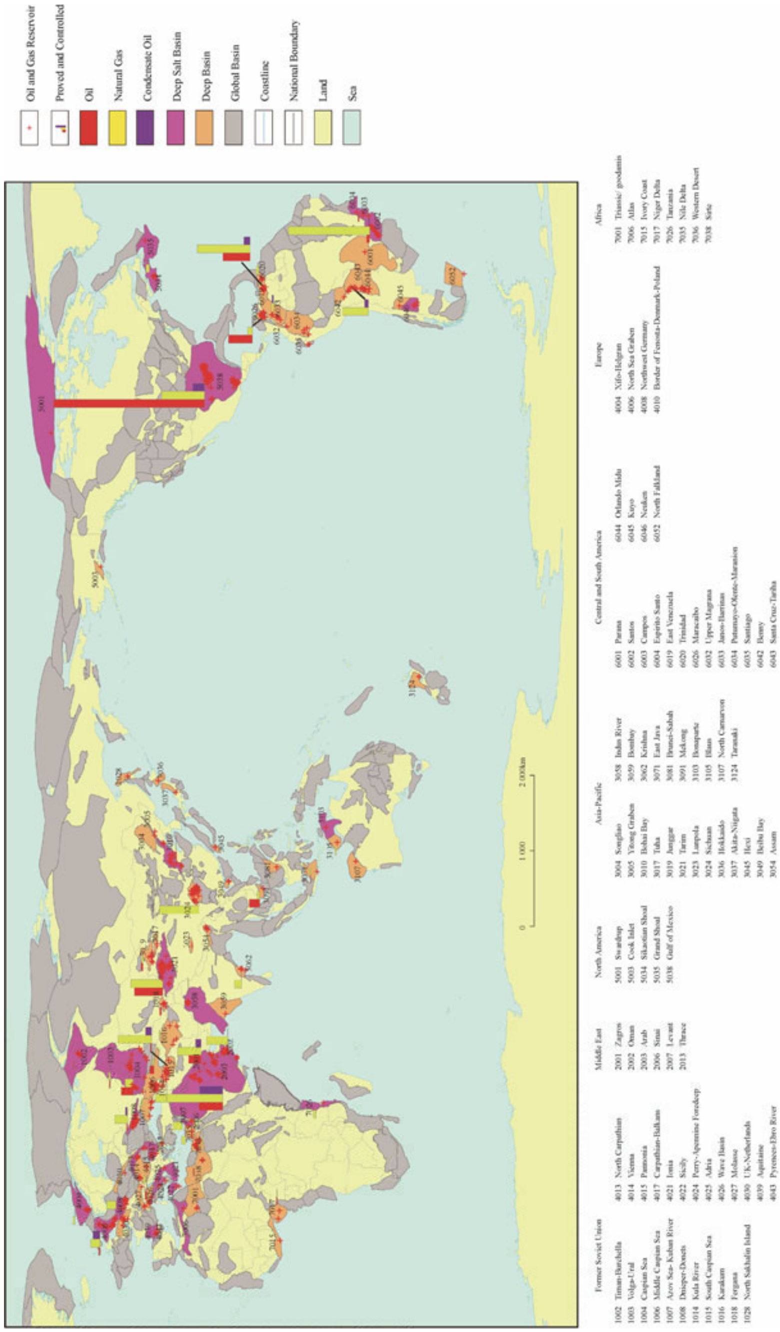

Fig. 1.2 Global distribution of deep petroliferous basins and deep reservoirs (Guoping and Binfeng 2014)

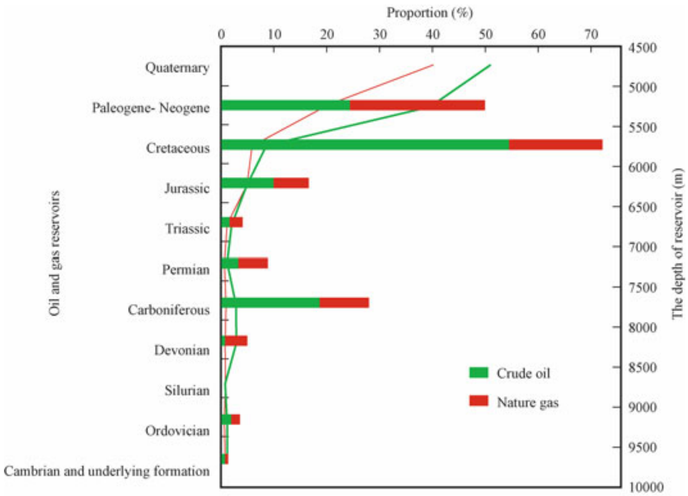

Fig. 1.3 Distribution depth and strata of global deep oil and gas reservoirs

of the total reserves respectively. The deep oil and gas reserves concentrate in the Mesozoic and Cenozoic strata, especially the Cretaceous, Paleogene and Neogene strata, in which the deep Cretaceous oil and gas reserves account for 48 and 24% of the total reserves, and the Pleogene and Neogene reserves account for 21 and 34%. At the same time, with the aging of the reservoir, the proportion of deep natural gas in the total amount of deep oil and gas increases.

Generally speaking, there are some characteristics in these basins: (1) the deposit thickness is generally more than 8 km, even 20–25 km in some basins, such as the North Caspian Basin and the South Caspian Basin with the deposit thickness of more than 25 km; (2) most of the basins are located in ancient hydrocarbon areas, which also have developed a large number of middle-shallow hydrocarbon reservoirs, such as Gulf Coast Basin in the United States and Pre-Caspian Basin in the former Soviet Union, which are famous petroliferous basins and have been developed for many years (Yu et al. 2012); (3) most of the deep reservoirs are developed below 5500–6000 m. At present, the deepest gasfield in the world is the Mills Ranch Gasfield in Anadarko Basin, and the deepest gas producing stratum is the dolomite stratum in Arbuckle Formation of Cambrian-Silurian, with a depth of 7965 m. (4) these basins usually have low geothermal gradient and high abnormal pressure. In terms of basin types, the discovered deep oil and gas fields are mainly concentrated in the passive continental margins, foreland basins, middle-lower combinations of craton basins and rift basins (Table 1.1). The deep oil and gas fields in the global passive marginal basins are mainly found onshore and deep-sea basins of Mexico Gulf, Santos Basin in Brazil, Levitan Basin in the eastern Mediterranean, Browse Basin in the northwestern shelf of Australia, Niger Delta Basin in Africa, and Krishida-Gedavari Basin in the eastern sea of India. These deep oil and gas fields are mainly distributed in deep and ultra-deep water areas and composed of sandstone reservoirs in Mesozoic and Cenozoic.

Table. 1.1 Distribution of major oil and gas exploration fields in deep strata of the world

Exploration field	Basin		Reservoir	Buried depth of reservoir (m)	Typical oil and gas fields
Middle-lower Assemblages of Craton Area	Cratonic Margin	Arabian Platform Basin	Sandstone of Devonian Juaf Formation	4900	Ghawar Oilfield
			Jurassic Carbonate Rocks	4570–4920	Umm Niqa Gasfield
		Amu Darya Basin	Jurassic Reef Limestone	4295–4795	Yashlar Gasfield
	Intracatoinc Basin	Pre-Caspian Basin	Carboniferous Under-salt Limestone	3900–4600	Casagan Oilfield
		Permian Basin	Silurian Carbonate Rocks	4785–5715	Vermejo/moore-Hopper Gasfield
Foreland Basin	Zagros Fold Belt		Mesozoic Carbonate Rocks	4500–5200	Ramin Oilfield, Marun Gasfield
	Anadarko		Silurian-Devonian Carbonate Rocks	5395–6001	Mills Rance Gasfield
	East Venezuela		Cretaceous Sandstone	4650	Santa Babara Oilfield
	Chaco		Devonian Sandstone	4410–5037	San Alberta Gasfield
	Deep South Caspian Sea		Pliocene Sandstone	5600–6265	Shah Deniz Gasfield
Passive Marginal Basin	Drift Sequence	Surest, Mexico	Jurassic-Cretaceous Carbonate Rocks	3900–4720	Bermudez Oilfield
		Deep sea in the Gulf of Mexico	Turbidite Sandstone in Paleogene Deep Sea	>8000	Tiber Oilfield
		Krishida-Gedavari	Cretaceous Turbidite Sandstone	4205–5061	Deen Dayal Gasfield

(continued)

Table. 1.1 (continued)

Exploration field	Basin		Reservoir	Buried depth of reservoir (m)	Typical oil and gas fields
	Rift Sequence	Blaus	Middle Jurassic Sandstone	5012	Poseidon 1 Oilfield
		Santos, Brazil	Cretaceous Shell Limestone	4900	Lula Oilfield
Rift Basin	Central Graben of North Sea Basin		Jurassic Sandstone	5350–5630	Elgin-Franklin Gasfield
	Bedrock in Jiulong Basin		Bedrock Fracture in Mesozoic	4500–5500	Bach Ho Oilfield

Deep craton oil and gas fields are mainly composed of reef carbonate reservoirs and stratigraphy-structure traps, which are mainly distributed in Arabian Platform Basin in Middle East, the under-salt strata of Pre-Caspian Basin, the under-salt strata of Amu Darya Basin and Permian Basin in the United States. Deep oil and gas fields in foreland basins mainly develope carbonate rocks and sandstone reservoirs, which are dominated by structural traps related to folds and thrust faults, such as the Zagros fold belt, Malacaibo Basin in Andean Foreland, the east Venezuela Basin, Chaco Basin, South Caspian basin, Anadarko Basin, etc. The deep oil and gas fields in the rift basins are mainly distributed in the central North Sea Graben and Vienna Basin, and the deep sandstone reservoirs are characterized by high temperature and high pressure.

1.1.3 Formation Conditions of Global Deep Oil and Gas Fields

The hyrdrcarbon geology theories and understandings developed in hydrocarbon exploration of middle-shallow strata are limited in deep hydrocarbon exploration. According to the classical petroleum geology theory (Tissot and Welte 1978; Wenzhi et al. 2005), most of the discovered oil in the world exists within the “liquid window” (the temperature range from 65.5 to 149 °C), above which oil will be replaced by natural gas. However, deep oil and gas exploration has confirmed that the temperature at which oil exists is well above the limit (Jincai et al. 1999). In some reservoirs, liquid hydrocarbon accumulations can still exist in the oil fields at 295 °C, such as the North Sea Oilfield, the Washington Oilfield in America, the Barr Lake Oilfield, the Paladin Oilfield, the Leyik Oilfield and Bieer Oilfield in Mexico Gulf Basin, the Marun Oilfield in the Persian Gulf, and even the Bla Sea reservoir in the Pre-Caspian Basin in Russia. The experiences and theories summarized in the exploration in deep oil and gas fields by making a rapid development of theoretical research and a full understanding of generation, migration, preservation and distribution in deep oil and gas reservoirs can lead to a better exploration of oil and gas.

So far, a great deal of researches on deep oil and gas exploration have been made by many scholars (Wenzhi et al. 2007; Wenhui et al. 2009; Pang Xiongqi et al. 2010). These researches mainly have focused on the following aspects: the temperature of oil and gas in deep strata, the material base of deep oil and gas reservoir formation, the stability of deep oil and gas, main controlling factors of deep reservoir property, the influence on oil and gas accumulation caused by abnormal high pressure and the analysis of geological conditions in typical deep oil and gas fields. Through the analysis of the reservoirs geological factors in many global deep basins, the following conditions are required for the formation of deep oil and gas fields.

(1) High-quality source rocks

Like the oil and gas in middle-shallow strata, as the material basis, the source rocks with organic matters are also needed in deep oil and gas reservoirs for hydrocarbon generation. The existence of deep source rocks is an indispensable condition for the formation of deep reservoirs. The ultra-deep source rocks with high content of organic carbon in the petroliferous basins distributed widely and the it is mainly composed of terrigenous clastic rocks and carbonate rocks with the organic carbon content from 0.25 to 6%. The organic carbon content of the ultra-deep source rocks is mainly controlled by the sedimentary facies and the organic matter and has no relation with the burial depth. In addition to temperature and pressure, the maturity of the ultra-deep source rocks is related to the rate of the basin. Compared to the basin with essentially constant subsidence, the mature period of the source rocks with late-rapid subsidence is later, and the rate of hydrocarbon generation is higher.

(2) Good reservoir-cap combination

Many types of reservoirs, such as the pore type, fracture type, karst cave-fracture type, pore-fracture type and other types, exist in deep reservoirs of clastic rocks and carbonate rocks. Compared to the reservoir in shallow-middle depth, the porosity of the ultra-deep reservoir is not relatively low, land mainly composed of secondary pore. The reservoir property of the ultra-deep reservoir is not only controlled by the pressure and temperature, but also the stress. Under the overpressure environment, the compaction, cementation and dissolution are reduced, so the reservoirs with relatively high porosity and permeability are developed in the ultra-deep reservoirs. In the ultra-deep oil and gas reservoirs, the proportion of gas reservoirs and condensate gas reservoirs is obviously increased. High-quality reservoirs can be developed in the deep strata and filled by oil and gas under the conditions of favorable sedimentary facies, supergene weathering and leaching, dissolution of cement and dolomitization in diagenesis, abnormal high pressure, early oil and gas injection and fracture development.

In deep reservoirs, the existence of good reservoir-cap combination, especially regional caprock, is the key controlling factor of preservation as the hydrocarbons are easily lost upward or cracked into gas due to the deep depth and high temperature. The high-quality caprocks of ultra-deep reservoirs are mainly salt rock and mudstone. With the characteristics of compactness, deformability and strony toughness, the salt rocks are the best cap rocks for ultra-deep reservoirs, especially for large-scale reservoirs, such as Tengiz Oilfield in Pre-Caspian Basin (Huangjuan et al. 2016). The reservoir scale may increase with the depth if there are high-quality caprocks in the basin.

(3) Abnormal pressure

The statistics of global deep oil and gas show that the abnormal high-pressure are common developed in the areas where deep oil and gas accumulated, and overpressure controls both the thermal evolution of deep source rocks and the porosity and permeability of reservoirs (Hunt 1990; Caillet et al. 1997; Wilkinson et al. 1997; Haiqing et al. 1998; Fang et al. 2002; Hao et al. 2007; Jiarui et al. 2016).The deep source rocks entered the stage of quasi-metamorphism in the traditional model may be still in the favorable stage of hydrocarbon generation and expulsion, and become the effective source rocks for hydrocarbon accumulation in deep strata, as the increased abnormal pressure can restrain obviously the thermal evolution of organic matter and the generation of oil and gas. The development of overpressure can maintain the porosity and permeability of the deep reservoir and provide reservoir conditions for deep oil and gas accumulation, because the effective stress of the overpressure system is reduced, which result in the weakening of compaction and suppression of pressure dissolution, and make the deep reservoir with higher porosity and permeability.

(4) Favorable tectonic setting

Special oil and gas reservoirs can be formed on the special tectonic setting as the source rocks and reservoir-cap combination of deep oil and gas are controlled by the development and type of the basin, as well as the filling of the sedimentary facies belts (Jianghai et al. 2014). Passive continental margin, foreland basin, middle-lower assemblage of craton basin and rift basin are favorable basins for the development of deep oil and gas fields, because: (1) a thick sedimentary layer of the material conditions for deep hydrocarbon generation and preservation can be formed; (2) abnormal high pressure can be easily formed, which restrains the generation and expulsion of hydrocarbons and makes the depth of oil generation window decreases, meanwhile, the overpressure in the reservoir makes the reservoir maintain better porosity and permeability conditions; (3) these types of basins are prone to form a large number of fractures, which increase the porosity and permeability of the reservoirs and promote the expulsion and accumulation of oil and gas; (4) a large number of structural traps in rift basins and foreland basins are formed, especially those related to faults and anticlines which can form good trap conditions.

Nowadays, the proportion of deep oil and gas fields in total reserves is increasing. In the United States, the average hydrocarbon reserves in deep strata have exceeded that in middle-shallow strata. In Russia, the average hydrocarbon reserves in deep strata are equal to that in middle-shallow strata (Shixin et al. 2005). It can be predicted that the total hydrocarbon reserves of deep strata will be greatly increased with the technology development of deep hydrocarbon exploration.

1.2 Exploration and Challenges of Onshore Deep Oil and Gas Fields in China

Deep oil and gas exploration in China is just beginning. In recent years, with the continuous effort on oil and gas exploration in deep and ultra-deep strata, a series of large-scale oil and gas fields have been discovered and it shows great exploration potential. At the same time, a series of new understandings and developments have been made in the generation and preservation of deep oil and gas, reservoir formation mechanism, evaluation and exploration potential of hydrocarbon resources, and exploration engineering technology. The research of deep oil and gas geology is incomplete yet, and the theories that can be directly responsible for the guidance of hydrocarbon exploration and production have not been formed. Lots of key geological problems and evaluation technologies are still under exploration and need to be solved urgently.

1.2.1 Exploration History and Current Situation of Deep Oil and Gas Fields in China

The exploration of deep oil and gas reservoirs in China began in the 1970s and 1980s. In 1966, the first deep well Songji 6 (4719 m) was drilled in China, and the first ultra-deep well Nvji (6011 m) was drilled in 1976, and the well Guanji (7175 m) was drilled in 1978. The important information of deep strata in the valuable deep wells laid a solid foundation for the geology of deep oil and gas in China.

In the late 1980s, the research on deep strata were carried out by petroleum geologists since the development of eastern major oilfields gradually entered the middle-late stage (Shixin et al. 1999; Zhiyi 2005; Zhongjian and Hui 2009). During this period, after several exploration meetings in the Northeast of China and Tarim Basin, breakthroughs were made in well Shacan 2 and well Kela 2, and high-quality unitized oilfields such as Lunnan, Tazhong, Donghetang and Hudson were discovered. And the theories of deep oil and gas have been developed rapidly since the exploration potential of deep oil and gas has been valued by explorationists.

In the twenty-first century, with the continuous increase of national energy demand and the depletion of oil and gas production in middle-shallow strata, China and many oil companies have increased their support for deep oil and gas geological research and exploration and production, as deep oil and gas play an important role in the development of hydrocarbon industry and the increase in reserve and production. Mang “973” projects and national key hydrocarbon projects have been set up to promote the development of deep hydrocarbon geology. A series of theories which are important for deep oil and gas exploration are put forward by researchers in hydrocarbon geology, such as the “successive gas generation” theory of organic matters in the study of source rocks, “bimodal pattern” theoretical model of hydrocarbon generation for high-overmature source rocks, the theory of multiple hydrocarbon generation for marine source rocks (Zecheng et al. 2002; Wenzhi et al. 2005; Jinxing et al. 2008; Zhaoyun et al. 2009; Wenhui et al. 2009, 2012). In the reservoir research, it is proposed that the bedding karstification and interlayer karstification are the important generation mechanism of large-scale effective reservoirs in the ancient carbonate rocks. Under special geological conditions, the deep clastic rocks develope abnormal high-porosity interval and secondary-porosity zone, and volcanic rocks develope two types of effective reservoirs, primary reservoir and secondary-weathering reservoir. In the research of hydrocarbon accumulation, it is proposed that the liquid window can be maintained for a long time through progressive burial and the coupling of annealing and heating, meanwhile several “golden zones” of exploration can be developed in deep superimposed basins with multiple hydrocarbon source kitchen, multistage reservoirs, multistage accumulation and late availability. The hydrocarbon reservoirs of deep strata in superimposed basin and marine strata greatly enrich the theory of deep oil and gas geology, with the characteristics of “hydrocarbon controlled by source rocks and cap rocks, and hydrocarbon accumulation controlled by slope”. At the same time, a number of academic works focused on deep oil and gas exploration have been published one after another, including representative works such as “Deep gas fields in China”, “Deep petroleum geology in eastern China”, “Deep fluid activities and effects of oil and gas accumulation” (Jin Hansheng 2002; Tao 2002; Zhijun et al. 2007; Xiaorong et al. 2016). These monographs have studied the geological conditions, the hydrocarbon generation and evolution, the accumulation model and distribution of middle-large deep oil and gas fields in China from different perspectives.

In recent years, a series of significant breakthroughs and discoveries gas have been made in deep oil and gas exploration of key petroliferous basins in China. Marine carbonate oil and gas fields such as Lunnan, Tahe and Tazhong, and continental clastic gas fields such as Dabei and Keshen are found in the Tarim Basin (Zhijun 2005; Yuzhu 2008; Zhongjian and Hui 2009; Guangyou et al. 2010; Zhengzhang et al. 2011; Wenzhi et al. 2012; Chunchun et al. 2017). Among which, Donghetang Oilfield is the deepest one, with a maximum reservoir depth of 6130 m, and the proved reserves of 3251×10^4 t. In addition, the reservoirs with buried depth more than 5000 m exist in Yaha Oilfield, Sangtamu Oilfield, Yangtake Oilfield, Tahe Oilfield, and Yangtake Gasfield. The maximum buried depth of Carboniferous volcanic reservoir in Shixi Oilfield, Junggar Basin is 4530 m (Jinghong et al. 2011). The deep reservoirs with buried depth of 3500–4000 m are continuously found in Karamay Oilfield, Chepaizi Oilfield and Mabei Oilfield of northwestern Junggar Basin, Hutubi Gasfield, Kayindike Oilfield in the south of Junggar Basin, Mosuowan Uplift and Mobei Uplift in central Junggar Basin. Shunbei Oilfield, which was discovered in 2016, has a resource of 17×10^8 t, including oil of 12×10^8 t and natural gas of 5000×10^8 m^3, with an average burial depth of over 7,300 m, and the characteristics of ultra-deep, ultra-high pressure and ultra-high temperature. The discovery of Shunbei Oilfield is a major breakthrough in domestic deep oil and gas exploration. Large-scale carbonate gas fields such as Puguang, Longgang and Gaoshiti have also been found in Sichuan Basin (Jizhong and Shengji 1993; Wenhai 1996; Yongsheng et al. 2007; Shugen et al. 2008; Longde et al. 2013; Guoqi et al. 2013; Jinhu et al. 2014). The main reservoir of Wubaiti Gasfield is composed of dolomite in the middle Huanglong Formation of Carboniferous strata (Ping 1998; Rongcai et al. 2014), with the maximum buried depth of 4595 m. It is a large-scale stratum-structure gas reservoir, with proved reserves of 587.11×10^8 m^3. The deepest gas-bearing structure in China is Laojunmiao Gasfieldin Sichuan Basin, with a depth of 7153.5–7175 m. The main reservoir of Jingbian Gasfield in Ordos Basin is Ma5 member of Ordovician

Majiagou Formation, part of which is buried below 3500 m, with the maximum buried depth of 3600 m. The exploration of deep oil and gas reservoirs in Bohai Bay Basin had begun in 1977. The geological reserves of 73×10^4 t^3 were obtained in well Ninggu 1, dolomite Buried Hill in Lining Oilfield, with the maximum buried depth of 5,300 m. At present, more than 100 deep oil and gas reservoirs have been found, and the proved geological oil reserves are more than 2×10^8 t. The deep strata of Songliao Basin mainly refer to the strata below Quantou Formation, with the buried depth more than 3000 m. For example, the buried depth of Changde Gasfield in the west slope zone of Xujiaweizi fault depression is nearly 3600 m. In recent years, a series of breakthroughs have been made in the exploration of deep volcanic natural gas in Songliao basin. The daily production of well Xushen1, well Weishen5, well Zhaoshen10 and well Wangshen1 in Xujiaweizi fault depression exceeds 10×10^4 m^3, which guides to a gasfield with reserves of more than 100 billion cubic meters.

1.2.2 Exploration Trend of Deep Oil and Gas in China

Nowadays, the oil and gas exploration onshore has been continuously developed to deep and ultra-deep strata. Major exploration breakthroughs have been made in the eastern region below 4500 m and the western region below 6000 m. The deep strata has become a major replacement field for onshore oil and gas exploration in China since the exploration depth extended 1,500–2,000 m down. Taking CNPC as an example, the average depth of exploratory wells increased from 2296 m in 2000 to 3190 m in 2018, with an increase of 894 m. The depth of exploratory wells in the east of China has been increased continuously, and has exceeded 6000 m, such as 6027 m in well Niudong 1 in 2011. While the depth of exploratory wells in the central and western regions of China has increased obviously, which has exceeded 8000 m, such as 8023 m in Keshen 7 well in 2010 and 8060 m in Wutan 1 well in 2018. Since 2000, the proportion of increased reserves of deep oil and gas of CNPC has been on the rise. Before 2010, the proportion of deep oil reserves averaged 6.8%, and since 2010, the proportion has increased to 13.4%. Before 2010, the proportion of deep nature gas reserves averaged 31.6%, and the proportion has increased to 57.2% since 2010 (Fig. 1.4).

At present, domestic onshore deep oil and gas exploration is in the period of breakthrough and discovery, more deep oil and gas fields are yet to be explored and developed. Taking CNPC as example, 14 important discoveries have been made in recent deep oil and gas exploration, including 5 oil discoveries and 9 natural gas discoveries. In the exploration area of carbonate rocks, two reserve areas with a scale of more than 5×10^8 t were found in Tabei area and Tazhong area of Tarim Basin. A reserve area with a scale of more than 3000×10^8 m^3 was found in Longgang Reef Beach of Sichuan Basin. In the exploration area of clastic rocks, gas fields with a scale of trillion cubic meters were found in Kuqa area of Tarim Basin, Songliao Basin and deep potential strata of Qikou area in Bohai Bay Basin. In the exploration area of volcanic rocks, two gas fields with a scale of 100 billion cubic meters in Xushen area of Songliao

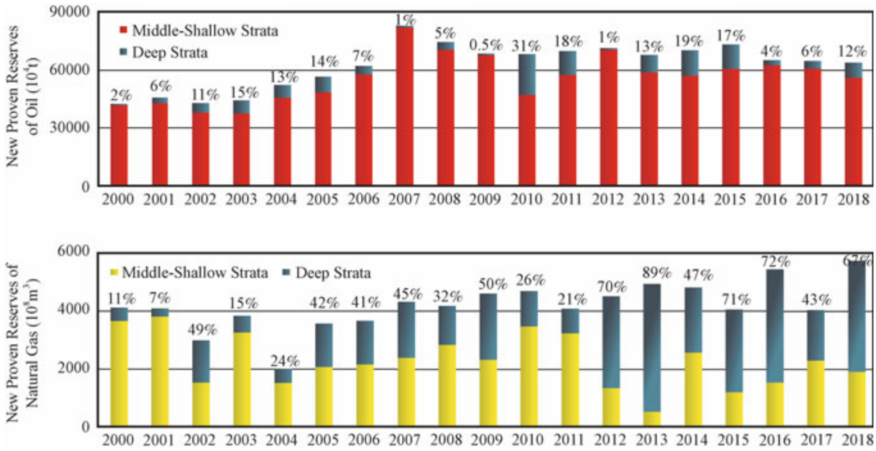

Fig. 1.4 Distribution of new proved reserves of oil and gas in China since 2000

Basin and Kelameili area of Junggar Basin, and an oilfield with a scale of 5000 × 10^4 t in Niudong area were found. However, there are abundant deep oil and gas resources in China, including deep oil resources (>4500 m) of 304.08 × 10^8 t, accounting for 28% of the total national oil resources; deep natural gas resources (>4500 m) of 29.12 × 10^{12} m^3, accounting for 52% of the total national natural gas resources. Within China's petroleum mining claims, deep oil resources amount to 144.37 × 10^8 t, accounting for 29% of China's total oil resources, and the deep natural gas resources amount to 26.73 × 10^{12} m^3, accounting for 56% of China's total oil resources. In terms of remaining hydrocarbon resources, the remaining oil resources in deep strata are 128.09 × 10^8 t, and the proved rate is only 11.3%, while the remaining gas resources in deep strata are 23.11 × 10^{12} m^3, and the proved rate is 13.5%, which is far lower than that in middle-shallow strata. The above studies indicate that the deep strata may be an important area for reserve and production increase.

1.2.3 Geological Characteristics of Deep Oil and Gas in China

China is rich in deep oil and gas resources and has great exploration potential. However, the domestic petroliferous basins have their own characteristics.They are mostly developed on the small cratonic blocks, with small scale and poor stability, and they can creat the conditions for the formation and accumulation of oil and gas resources, as the sedimentary and structural differentiation developed in platform through the strong reforming and destruction caused by the sedimentary environment with great lateral change. At the same time, because of the early formation of craton plate and multistage of tectonic evolution, the domestic petroliferous basins