# 1 Introduction

**Abstract**

By summarizing and comparing the basic geological conditions of shale gas development in North America and China, this chapter finds that the development of gas-bearing shales in North America is concentrated, and the resource type is single. In contrast, the development of shale in China involves more layers with more resource types, and basic research has been performed in shales developed in marine–terrestrial transitional facies and terrestrial facies. A comprehensive analysis of the existing research on lithofacies paleogeography and its role in the development of the world's oil and gas industry indicates that lithofacies paleogeography research and mapping methods can preliminarily clarify the connection between the sedimentary environment and distribution of energy and mineral resources.

**Keywords**

Research status • Shale gas • Lithofacies paleogeography • Comparative study • North America; China

Shale gas is an important unconventional natural gas resource (Ye and Zeng 2008). With the continuously growing social demand for clean energy, increasing natural gas prices, deepening understanding of shale gas reservoir formation conditions, and advancements in drilling technologies, shale gas exploration and development have expanded from North America across the world (Du et al. 2011). In 2018, U.S. shale gas production reached $6669 \times 10^8$ $m^3$, accounting for 63.4% of the total natural gas production, and this high production changed the global natural gas supply pattern (Jiang et al. 2020). Shale gas has emerged as a research hotspot in the exploration and development of unconventional oil and gas resources worldwide, and accelerating the exploration and development of shale gas resources has become a focus of the major shale gas resource countries (Du et al. 2011). With the rising demand for energy, increasing energy pressure and environmental awareness in China, the exploration and development of shale gas resources must be accelerated (Jiang et al. 2020). Consequently, large-scale basic geological investigations of shale gas are being performed in China.

Unlike the USA and Canada, which are characteristic of concentrated shale gas development strata and single type of shale gas resources, China exhibits shale gas development strata that are distributed across geological historical periods, including Cambrian, Ordovician, Silurian, Carboniferous, Permian and Jurassic. Moreover, many types of shale gas resources exist, including marine, marine–terrestrial transitional and terrestrial facies. Compared with North America, Chinese shale gas resources are characterized by large geological ages, large burial depths, high degrees of thermal evolution and complex tectonic and geomorphic conditions (Sun et al. 2020). In the general geological investigations in the 11th and 12th Five-Year Plans, the distribution areas of marine, marine–terrestrial transitional and terrestrial source rocks in China were preliminarily estimated to be as large as $300 \times 10^4$ $km^2$, $200 \times 10^4$ $km^2$ and $280 \times 10^4$ $km^2$, respectively (Zhang et al. 2011). From the perspective of geographical distributions, high-quality marine source rocks are mainly distributed in Southern China, especially the middle-Upper Yangtze region (Liu et al. 2004; Li et al. 2009d), and the lithology mostly includes siliceous shale, black shale, calcareous shale and sandy shale. Most of the high-quality source rocks pertain to siliceous and black shale. This area is a frontier for geological investigation, exploration and development of shale gas in China (Long et al. 2009). The source rocks of the marine–terrestrial transitional facies are mainly distributed in Southern China, Northern China and Junggar in Northwest China. These rocks are scattered but exhibit a high resource potential. The source rocks, which are mostly siliceous shale, coal-bearing black shale, coal-bearing calcareous shale and silty shale, are important types of shale gas resources and gaining


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considerable attention in China. The distribution of terrestrial source rocks is similar to that of marine–terrestrial transitional source rocks, which are distributed in the three major plates in China. Among the terrestrial source rocks, the Jurassic system in Southern China has been the focus of shale gas resource research, followed by the Middle Cenozoic strata in Northern China and a small amount of source rock in the Junggar Basin and the Qinghai-Tibet Plateau. The lithology mainly includes a set of black shales, calcareous shale and silty shales of lacustrine facies.

Since the initial geological survey of shale gas in China and the extensive exploration and development of shale gas in key areas, many geologists have conducted a considerable amount of preliminary research. From 2005 to 2009, the geological conditions of shale gas in Mesozoic hydrocarbon-bearing basins were analyzed with the source rock formations as the research objects, and the geological prospects of shale gas in these Formations were analyzed based on the distribution pattern of Paleozoic source rocks in the basin and outcrop area. Further comparison was performed considering the geological characteristics of the shale gas development Formations in the USA. Based on this research, the shale gas resource prospects in the Upper Yangtze region were analyzed, and the prospective areas were initially selected (Zhang et al. 2003, 2004, 2008a, b; Liu et al. 2004; Zhao et al. 2008; Ye and Zeng 2008; Zhang et al. 2008; Zou et al. 2009; Long et al. 2009; Li et al. 2009d; Cheng et al. 2009; Wang et al. 2009a, b, c). The 12th Five-Year Plan (2010–2015) corresponded to valuable breakthroughs in shale geological investigation and research in China. In the period 2010–2015, considering the basic geological characteristics of shale gas development in China, strategic surveys of shale gas resources were performed nationwide, the national shale gas resource potential was evaluated, and the favorable areas were selected (Zhang et al. 2009, 2010a, 2012b; Zou et al. 2009, 2010a, 2013a; Chen et al. 2009a, 2009b; Pan and Huang 2009; Li et al. 2009d, Wang et al. 2009a, b, c; Huang 2009a; Xu and Bao 2009; Li and Zhao 2009; Nie et al. 2009a, 2011a, 2011b, 2011c; 2012a, 2012b, c; Jiang et al. 2010; Zhang 2011; Duet al. 2011; Zeng et al. 2011; Chen et al. 2011a; Fu et al. 2011; He et al. 2011; Liang et al. 2012; Zhang et al. 2012b, 2013; Wu et al. 2013a; Wang et al. 2013; Zheng et al. 2013a; Li et al. 2014, 2015; Wang 2015; Jiao et al. 2015; Zhang 2015). Moreover, industrial breakthroughs in shale gas exploration and development were achieved through geological investigations and favorable area optimization. With expanding research on shale gas exploration, CNPC, Sinopec, Chongqing, Sichuan and Guizhou have successively established shale gas exploration companies or project departments to conduct basic geological investigations and research on shale gas resources in the Sichuan Basin and adjacent areas. CNPC has selected four favorable blocks: Weiyuan, Changning, Zhaotong and Fushun-Yongchuan (a cooperative block with Shell) in Southern Sichuan and Northern Yunnan-Guizhou and drilled more than 60 shale gas exploration wells, leading to significant exploration breakthroughs. High-yield shale gas flow has been observed in Well Yang101 in Fushun and Well Ning201 in Changning, and Well Wei201 represents the first drilled well for shale gas development. Sinopec has mainly focused on Fuling, Nanchuan and Qijiang in the Southeastern Sichuan Basin and Pengshui outside the basin. The organization has identified more than 50 shale gas exploration wells, achieved exploration breakthroughs in Fuling, Qijiang and Pengshui, established the Fuling National Shale Gas Exploration Demonstration Zone and discovered China's first shale gas field, the Fuling Shale Gas Field, with proven reserves of $106.75 \times 10^9$ $m^3$. In 2015, the Fuling National Shale Gas Demonstration Zone was successfully completed, with a production capacity and output of $5 \times 10^9$ $m^3$ and $31.68 \times 10^8$ $m^3$, respectively, accounting for 71% of China's shale gas production (Cai et al. 2021). In 2016, substantial exploration breakthroughs were made in other prospective areas, and as of 2020, 6 large and medium shale gas fields have been discovered in Fuling, Weirong, Changning, Weiyuan, Zhaotong and Yongchuan in the Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation of the Sichuan Basin (Zou et al. 2017; Cai et al. 2021) (Fig. 1.1), indicating that shale gas exploration in China has entered the industrialized and quasi-industrialized production stages. These achievements demonstrate the prospects for the exploration and development of shale gas in the Sichuan Basin and its peripheral area, which are expected to facilitate the growth of natural gas production in China.

Nevertheless, the shale gas geological investigations are limited, and a guiding ideology and key technical methods are lacking. According to the actual geological investigation results of shale gas in China, the reservoirs are characterized by multiple resource types, widespread distribution and high potential (Zhang 2011). From discovery to final industrial and commercial development, shale gas reservoirs have benefited not only from the development and deepened understanding of oil and gas geological theories, such as the discovery of micro/nanoscale pores and extension of non-Darcy seepage theory but also from the breakthrough and progress of industrial technologies, such as horizontal well development and multistage hydraulic fracturing technologies. In this context, the conduction of basic geological investigations of large-scale shale gas requires targeted knowledge and theoretical guidance of geological disciplines and the application of key technical methods.

Research on the regional geological background and related basic geological characteristics of shale gas development in China, such as the spatial distribution of

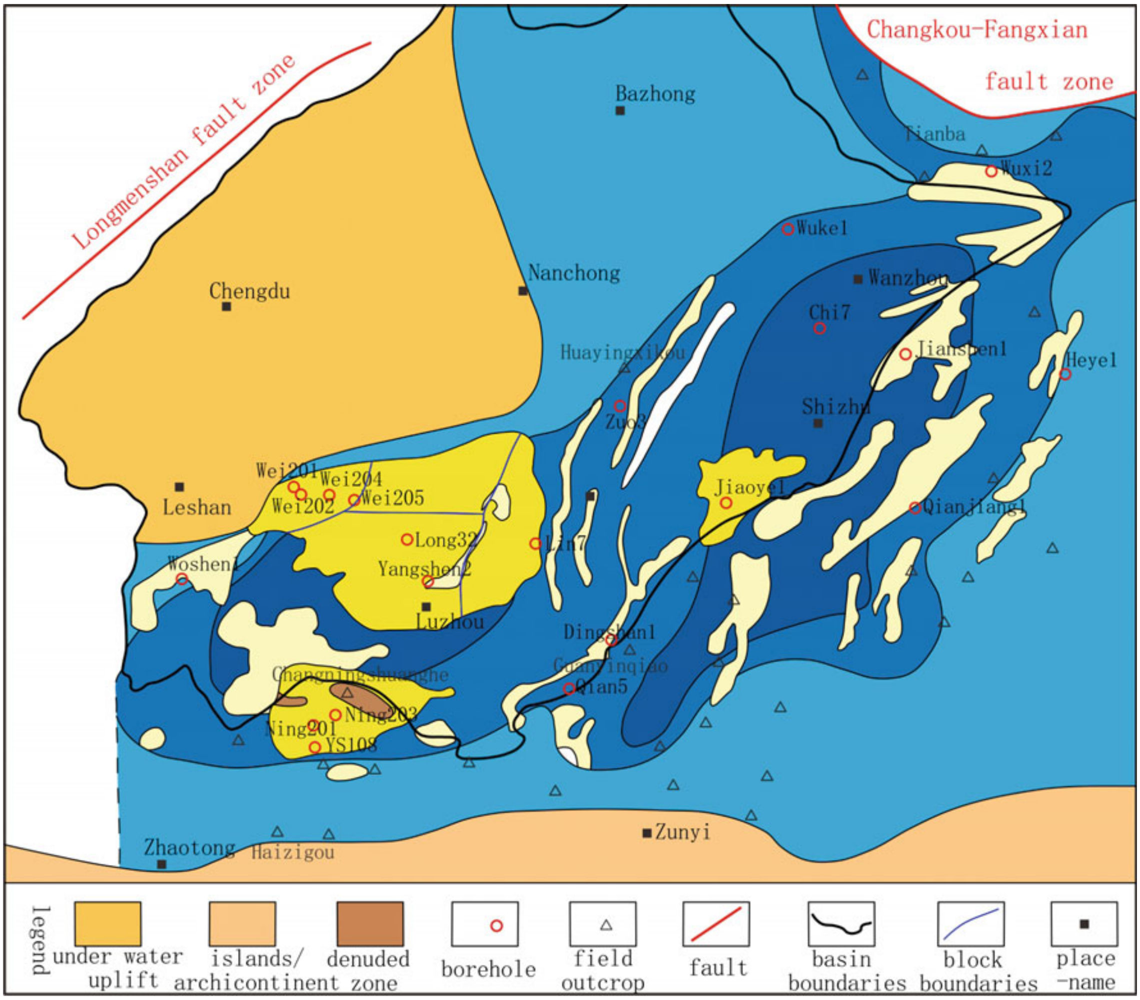


**Fig. 1.1** Key drilling spots for shale gas in the Wufeng Formation-Longmaxi Formation in the Sichuan Basin (Zou et al. 2017)

mudstones and shale; sedimentation and diagenesis; and reservoir characteristics, enrichment and accumulation, along with their evaluation and optimization, is still in the lag phase. The level of nationwide geological investigation for shale gas is low. Consequently, except for a few areas in the Sichuan Basin, no major breakthrough has been made in most areas yet. Moreover, except for the Wufeng-Longmaxi Formation, industrial production has been realized, necessitating the expansion of research in other regions. Despite the deepening of shale gas geological investigation and continuous improvement of research and exploration methodologies, the key technical methods have failed to address the requirements for accelerating production development. The main problems can be summarized as follows: Although many researchers have focused on shale gas, most of these studies were performed in certain areas or stratigraphic subdivisions, and only a limited number of studies have been performed on the development characteristics, enrichment and spatial distribution of the complete shale gas reservoir system. The research of sedimentary systems, sequence stratigraphic and petrographic paleogeography with source rocks is not systematic. Moreover, systematic and extensive research on the spatial and temporal distribution characteristics of organic-rich shale as source rocks and reservoirs must be performed using basic and operable key research methods and means. The formation mechanism of shale gas in depositional and diagenetic processes remains to be clarified, as the diagenetic minerals, diagenesis, diagenetic evolution and pore evolution of shale gas reservoirs have not been studied sufficiently. In addition, the formation mechanism of shale gas reservoirs has not been systematically explored.

In conclusion, the extent and research of shale gas geological investigations under the complex geological background of China are limited owing to the lack of integrated, systematic and unified technical approaches and basic geological theories. Through comprehensive comparative research, the authors believe that the key to shale gas geological investigation and development is to understand the basic geological characteristics and spatial distributions of the shale gas reservoir-source rocks, to understand the relevant background and to optimize the prospective, favorable and target areas. In other words, shale gas geological investigations have the following three objectives:

(1) To clarify the characteristics of source rocks, such as lithological characteristics, depositional environment, types and characteristics of sedimentary microfacies (lithofacies), organic matter contents and mineral compositions.
(2) To clarify the spatial and temporal distribution patterns of source rocks, including their thickness, burial depth, fine distribution and area.
(3) To optimize the prospective and favorable areas of shale gas reservoirs to provide a scientific basis for the exploration and development of shale gas.

Theoretically, the key to shale gas geological investigation and research is to focus on basic geological surveys and source rocks, which are the carriers of shale gas development and deposition, especially through lithofacies paleogeography and mapping. Another key aspect is to follow systematic and scientific approaches, use reasonable geological theories and identify critical research methods.

Based on the actual situation, the Southern Sichuan Basin and its adjacent region, which involve the Lower Cambrian Niutitang Formation and Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation, are key areas for shale gas geological surveys in China with promising shale gas development strata and considerable shale gas resource potential. Since 2008, the Ministry of Land and Resources, Chengdu Center of China Geological Survey, CNPC, Sinopec and related research and production units have performed geological investigations and exploration and development work in these regions, with the most significant achievement being the establishment of the first large shale gas field in China. According to the practical explorations, sedimentary (micro) facies, fine petrographic paleogeography and even sequence stratigraphy analyses and geochemistry and petroleum geology concepts can be used to perform the basic geological investigations of shale gas and promote the exploration and development of shale gas in later stages.

Accordingly, based on the authors' work experience and research, this book sublimates the concepts of sedimentology, lithofacies paleogeography, geochemistry and other related theories as guidance to examine shale gas carrier-source rocks. We emphasize that the geological survey of shale gas must be guided by lithofacies paleogeography and its related mapping methods, which can facilitate research on shale gas formation, spatial distribution characteristics, enrichment patterns and optimization of areas at different scales from macroscopic to microscopic to ultramicroscopic. The use of this approach for shale gas geological investigations and exploration and development studies is demonstrated and supported by an example pertaining to the research of gas-bearing formations, namely the Wufeng Formation-Longmaxi Formation in the Southern Sichuan Basin and adjacent areas. This book can provide scientific and reliable guidance for ongoing large-scale shale gas geological investigations and future exploration and development activities in China.

## 1.1 Current Research Status

According to the definition of petrology, clay rocks refer to sedimentary rocks dominated by clay minerals (content greater than 50%) (Zhao and Zhu 2001; Jiang 2003). Clay rocks that solidify into rock are known as mudstone and shale. Mudstone and shale are rocks with particle sizes of less than 0.0039 mm (i.e., < 4 μm) and composed mainly of clay minerals. In contrast, fine-grained sediments are clay- and silt-grade sediments with particle sizes less than 62 μm and mainly contain clay minerals, silt, carbonate, organic matter, etc. (Schieber and Zimmerle 1998; Aplin and Macquaker 2011). Jiang et al. (2013) referred to sedimentary rocks composed of fine-grained sediments as fine-grained sedimentary rocks or argillaceous rocks. Among these rocks, the rocks with developed and undeveloped lamination are known as shale and mudstone, respectively. The sizes of clay and silt particles are less than 4 μm and between 4 and 62 μm, respective. Since clay and silt particles are difficult to distinguish visually, argillaceous rocks are generally considered to be a mixture of clay and silt. In addition, fine-grained sedimentary rocks are widely distributed, accounting for approximately 2/3 of sedimentary rocks (Macquaker and Adams 2003; Aplin and Macquaker 2011), which is consistent with the proportion of clay rocks in sedimentary rocks reported by Chinese scholars such as Liu (1980) and Jiang (2003). The rocks defined as clay rocks by Chinese scholars may be consistent with the fine-grained sedimentary rocks classified abroad, although they are limited in terms of structural and compositional constraints. Shale gas reservoirs usually include argillaceous rocks, marls, sandstones and carbonate rocks (Zhang et al. 2008b; Bust et al. 2013). Therefore, the term "shale" in shale gas is typically used to represent a geological formation rather than the lithology (Bust et al. 2013). Moreover, shale gas formations actually consist mainly of fine-grained sedimentary rocks rather than muddy shales, but the lithology of shale gas formations is still collectively referred to as "shale" according to present research practice.

The deposition and diagenesis of fine-grained sediments in shale is a weak field of research in sedimentology and even geology due to the small particle size, difficulty of observation and limitations of ultramicroscopic experimental conditions. The study of fine-grained sedimentary rocks in shale gas formations can facilitate the analysis of sedimentary rock genesis and depositional environments and has important petroleum geological significance. In the hydrocarbon system, shale typically acts as a source rock or cap rock, generating hydrocarbons that migrate to reservoirs with superior physical properties or preventing the diffusion of hydrocarbons in the reservoir. The discovery of shale gas indicates that shale has dual characteristics as a source rock and reservoir.

The research and development of shale gas has a history of nearly 200 years. The USA was the first country to conduct shale gas exploration and commercial development. The development of shale gas in the USA can be divided into four major stages: the early exploration and development stage (1821–1975), geological theory and exploration technology research stage (1975–2000), rapid development stage (2000–2006) and rapid increase in production stage (2007 to present) (Wang et al. 2012b). The considerable history of research and exploration experience in the USA, coupled with the gradual enhancement of drilling and extraction technologies in its industrial processes, has transformed shale gas to one of the main energy supplies in the USA at present. According to the U.S. Energy Information Administration (EIA), the shale gas production in the USA in 2020 was $7330 \times 10^8$ m$^3$, accounting for approximately 80% of its total natural gas production. In 2019, the U.S. shale gas production increased by $957 \times 10^8$ m$^3$, accounting for 73% of the global natural gas production growth rate (Zou et al. 2021). The rapid growth of shale gas production in the USA and the satisfactory form of the entire industry are attributable to factors such as the natural gas market prices and long-term support of the state, industry authorities and associations (Wang et al. 2012b). The U.S. Government's advanced leadership pertaining to the "energy independence" strategy is the key to the success of the "shale oil and gas revolution" (Zou et al. 2021). However, from the perspective of shale gas, the innovations and progress in geological theories and methods related to shale gas research have ensured that the USA the only region worldwide to have commercialized the exploration and development.

Owing to the clean energy attributes of shale gas and the bottleneck of conventional oil and gas exploration and development worldwide, the research, exploration and development of shale gas has spread from North America, led by the USA, to the rest of the world, and emerged as a hot spot for energy exploration in the recent decade. The exploitation of shale gas resources is of significance for China, which has scarce oil and gas resources but widely developed organic-rich shales. Although shale gas research in China started relatively late, it has undergone three stages, including fractured reservoir exploration and accidental discovery (before 2005), basic research and technical preparation (2005–2009) and industrial breakthrough (2010) (Zou et al. 2010a; Wang et al. 2012b). At present, considerable shale gas research and exploration is being performed in China, focused on innovations in geological theories, geological investigations, exploration technologies and methods and more refined research at the microscopic scale. Notably, China officially initiated shale gas exploration and development after the USA and Canada. Despite starting at the base level, an annual shale gas production of $100 \times 10^8$ m$^3$ has been achieved in China, followed by a historic growth to $200 \times 10^8$ m$^3$ in two years at depths of 3500 m and a breakthrough discovery at depths of 3500–4000 m, which represent notable accomplishments in the history of China's natural gas development (Zou et al. 2021).

### 1.1.1 Current Status of Foreign Research

The history of the shale gas industry in the USA can be traced to 1821, when the first natural gas well was drilled by Mitchell Energy in the Devonian Durdirk Shale in Chautauqua County, New York (producing gas from an 8 m thick shale fracture at a well depth of 21 m) (Curtis 2002). Since then, shale gas has been used for home lighting in rural Fredonia. The most developed shale-gas-rich zone in the USA is the Barnett Shale reservoir in the Fort Worth Basin in Texas, the successful development of which has received widespread attention (Li et al. 2011a). Since Mitchell Energy and Development Corporation drilled the first well in the Barnett Shale in 1981, 20 years' worth of effort was expended to extract gas from impermeable shale using hydraulic fracturing techniques. The subsequent rapid decline in gas recovery from vertical wells led to the development of horizontal well technologies (Boyer et al. 2011). In 1992, the first horizontal well was drilled in the Barnett Shale gas reservoir, and the development of Barnett Shale was accelerated by advancements in the hydraulic fracturing techniques (Li et al. 2011a). The application of horizontal wells and hydraulic fracturing technologies has enabled the economic development of unconventional shale gas reservoirs (Rahm 2011). In 2008, Barnett Shale became the largest gas-producing formation in the USA, delivering 7% of the nation's natural gas (Boyer et al. 2011).

Organic-rich shales are widely distributed in 48 states in the USA (all states except Alaska and Hawaii), with gas resources ranging from $1483 \times 10^{12}$ m$^3$ to $1859 \times 10^{12}$ m$^3$ (Li et al. 2011a). Due to the low clay content and high brittle mineral content of marine shales, which are conducive for hydraulic fracturing, shale gas has been typically produced from Paleozoic silicon-rich marine sedimentary formations (Jenkins and Boyer 2008; Chalmers et al. 2012). Moreover, several researchers have focused on lacustrine organic-rich shale. For example, Zhang et al. (2012c) studied the Wealden Shale of Early Cretaceous lacustrine deposits in NW Germany using organic geochemical methods to reconstruct the depositional environment and performed 3D digital simulations of hydrocarbons to clarify the characteristics of shale gas in different areas.

1. Current status of shale gas exploration and development in North America

According to statistics, in the mid-1970s, the USA entered the stage of large-scale development of shale gas. In 2000, the USA had five shale gas basins: Antrim Shale in the Michigan Basin, Ohio Shale in the Appalachian Basin, New Albany Shale in the Illinois Basin, Barnett Shale in the Fort Worth Basin and Lewis Shale in the San Juan Basin, with geological resources of $12.85 \times 1012$ –$25.14 \times 1012$ $m^3$ and proven geological reserves of $6994.3 \times 108$ $m^3$ (Curtis 2002). Among these basins, Barnett Shale in the Fort Worth Basin is the largest shale-gas-producing area in the USA. The Newark East shale gas field discovered in the Fort Worth Basin in 1981 has emerged as the second-largest gas field in the USA, with annual shale gas production values of $217 \times 108$ $m^3$. By 2007, in addition to the five previously discovered shale-gas-producing basins in the USA, more than 20 basins, such as the Oklahoma Basin (Woodford Shale), Arkoma Basin (Fayetteville Shale) and Williston Basin (Bakken Shale) (Yan et al. 2009; Zhou et al. 2012) has been reported, with the Barnett, Marcellus, Fayetteville, Haynesville, Woodford, Lewis, Antrim and New Albany Shale associated with large-scale production.

With the success of shale gas exploration and development in the USA, regional exploration, investigation and testing of shale gas has also begun in Canada. Early exploration and development focused on the Middle Devonian Horn River Basin and Triassic Montney shale area in Northeastern British Columbia. In recent years, this exploration has gradually expanded to other provinces, such as Ontario and Quebec (Zhou et al. 2012). Preliminary predictions of shale gas resources in the Upper Cretaceous Wilrich Formation and its contemporaries, Jurassic Nordegg/Fernie Formation, Triassic Doig/Doig Phosphate/ Montney Formation, Exshaw/Bakken Formation and Devonian Ireton/Duvernay Formation in the Western Sedimentary Basin (eastern British Columbia and Alberta area), are approximately $2.83 \times 10^8$ $m^3$ (Yan et al. 2009), which demonstrates the potential of shale gas resources. The Canadian Society for Unconventional Gas (CSUG) considers the Colorado Shale, Jurassic and Paleozoic shales in the west (including the Bowser Basin in Northern British Columbia) and Devonian shales in the Southeast to have significant potential for development. In 2007, the shale gas production in Western Canada was approximately $8.5 \times 10^8$ $m^3$, with three horizontal wells showing a high daily production rate ($9.4 \times 10^4$–$14.2 \times 10^4$ $m^3$) (Yan et al. 2009). The Horn River and Montney shale gas play are present two of the largest shale gas reservoirs in Canada (Zhou et al. 2012).

2. Geological background of shale gas in North America

Along with technological innovations in shale gas development, US unconventional oil and gas companies are now focusing on the geological characteristics and regional geological background of shale gas reservoirs to increase the number of high-production wells and achieve a higher economic efficiency (Zhou et al. 2012). Shale gas basins in North America are mainly distributed in the areas in which passive continental margins have evolved into foreland basins and in the Paleozoic Craton terrane areas that are rich in conventional hydrocarbon resources (Montgomery et al. 2005; Pollastro et al. 2007; Li et al. 2009d; Zeng et al. 2011). The gas-bearing shale has various degrees of maturity, gas origins and lithofacies and complex depositional environments. The eastern petroliferous basins, such as the Appalachian Basin, Fort Worth Basin in the Gulf of Mexico and Western Canada Sedimentary Basin, are dominated by black shale, with inferences and interpretations of the depositional environment remaining open to debate (Li et al. 2009d). Loucks and Ruppel (2007) and Algeo and Barry (2008) proposed that the organic-rich black shale of the Devonian–Mississippian Barnett Formation in the Fort Worth Basin and central Appalachian basin corresponds to the restricted deep-water deposition in the foreland basin and was deposited below the storm wave-base and oxygen minimum zone (OMZ) at approximately 120–215 m with anoxic-anaerobic characteristics. These sediments are mainly composed of semipelagic ooze (from neritic shelves) and biological skeletal debris, and the sedimentation was largely accomplished by suspension mechanisms such as turbidity currents, mudflows and density currents, belonging to euxinic slope-basin facies. Biomarker data indicate that the main oil-generating Barnett Shale facies is marine in nature and was deposited under dysoxic, strong upwelling, normal salinity conditions (Hill et al. 2007a). The organic-rich mudstone in unit C of the Lower Jurassic Gordondale Formation in the Western Canada Sedimentary Basin (WCSB) was deposited on gentle slopes at water depths of up to 200 m (Ross and Bustin 2008). Hammes et al. (2011) investigated the geological background, depositional environment, stratigraphic characteristics and shale gas potential of the

Haynesville shale and indicated that the Haynesville shale was deposited in a euxinic and anoxic basin with a restricted environment. Romero and Philp (2012) studied the Woodford Shale in Oklahoma, USA, and concluded that high salinity conditions and water density stratification prevailed during the deposition of this formation.

These examples indicate that most of the black shales in North America were first deposited at high sea levels, and the nutrient-rich upwelling currents carried sufficient nutrients from deep-sea biogenic debris, resulting in high biological productivity and a strong reducing environment (Li et al. 2009d).

The analytical application of sedimentology and sequence stratigraphy is valuable in the regional search for shale gas resources and in predicting the shale gas potential. (Zhou et al. 2012). The sequence stratigraphic structure division of shale is less studied than that of coarse-grained clastic and carbonate formations (Bohacs 1998). Harris (2011) performed the sequence stratigraphic division of the Woodford shale in the Permian Basin based on sedimentological and geochemical characteristics and identified a second-order sea level decline cycle in the lower Woodford Formation, showing a lowstand systems tract with enriched total organic carbon (TOC). In contrast, the transgressive and highstand systems tract of the middle-upper Woodford Formation are not highly enriched in TOC. Hemmesch et al. (2014) studied the sea-level changes and sequence stratigraphic characteristics of the Upper Devonian Woodford organic-rich shale in the Palmyra Basin, West Texas and identified second- and third-order sea-level sequences based on shale layer characteristics. Abouelresh and Slatt (2012) classified the lower Barnett Shale in the east-central Fort Worth area into 1–7 depositional units and the upper Barnett Shale into 8–16 depositional units according to the rising and falling characteristics of sea level. The researchers indicated that the lower Barnett Shale was deposited in a low-energy, deep-water environment, slightly far from a terrigenous source area. In contrast, the upper Barnett Shale was deposited in an oxygenated shallower water environment and may have been influenced by tectonic periodic activities with frequent sea-level fluctuations. These aspects indicate that the division of sequence stratigraphy has a guiding significance for the development of organic-rich shales.

3. Petrological characteristics of gas-bearing shales in North America

(1) Rock types in Barnett Shale

The Mississippi Barnett Formation in the Fort Worth Basin is a classic shale gas system (Loucks and Ruppel 2007) whose geologic characteristics have been extensively studied in the recent decades. The Barnett Shale covers approximately 38 counties in the Fort Worth Basin in Texas, and the main gas-producing areas are located in the Northern and Southern parts of the basin. In the eastern part of the basin, the Barnett Shale unconformably overlies the Ordovician-age Viola Group and is overlain by the Pennsylvanian-age Marble Falls limestone (Jarvie et al. 2007).

Recognition of the different lithofacies is an important step in the evaluation of the gas in place, flow capacity and mechanical properties of Barnett Shale. The lithofacies vary in terms of the petrophysical and mechanical properties and organic content (Hickey and Henk 2007). The Barnett interval comprises a variety of facies but is dominated by fine-grained (clay- to silt-sized) particles. For example, the black shale of the Barnett Formation in the Fort Worth Basin consists mainly of calcareous siliceous mudstone and argillaceous lime mudstone, with intercalated thin beds of skeletal debris. Instead of detrital quartz, clay- to silt-sized microcrystalline quartz is the major component of the siliceous Barnett facies (Loucks and Ruppel 2007). Based on the analyses of porosity and organic geochemistry, a petrographic study of the conventional core Mitchell 2 T.P. Sims from Barnett has led to the identification of the following rock types: organic-rich black shale, fossiliferous shale, dolomite rhomb shale, dolomitic shale, phosphatic shale and concretionary carbonate (Hickey and Henk 2007). Abouelresh and Slatt (2012) analyzed Barnett Shale using cores, thin sections and SEM and reported several microsedimentary features that indicate that these common fine-grained rocks may have been transported and/or reworked by unidirectional currents. Six lithofacies were identified based on vertical facies transitions: (1) massive mudstone, (2) rhythmic mudstone, (3) ripple and low-angle laminated mudstone, (4) graded mudstone, (5) clay-rich mudstone and (6) spicule-rich mudstone. A number of sedimentary structures and textures indicate that a variety of current-related processes were active in sediment transport and deposition, likely including high-density flows, turbidity currents, storm currents and/or contour currents. The current-induced features of these facies likely included millimeter- to centimeter-scale cross- and parallel laminations, scour surfaces, clastic/biogenic particle alignment and normal- and inverse-size grading.

(2) Mineral composition of Barnett Shale

The mineral composition of the gas-bearing black shale is dominated by quartz, followed by clay minerals, carbonate minerals including calcite and dolomite and minor amounts of pyrite, feldspar and rhodochrosite. Moreover, this shale is characterized by a high organic matter content and traces of naturally occurring copper and phosphate minerals (Li et al. 2009d). The brittle mineral content is high, with quartz contents of 20–70% and carbonate mineral contents lower than 20% (Loucks and Ruppel 2007; Jarvie et al. 2007; Ross and Bustin 2008; Milliken et al. 2012). The clay minerals are mainly illite with some monazite (Bowker 2003), and the compositional maturity is relatively high. According to the minerals, textures, organisms and structures, the Barnett Shale can be grouped into three lithofacies: siliceous shale, clay shale and partly muddy carbonate (Loucks and Ruppel 2007; Jarvie et al. 2007; Ross and Bustin 2008).

The mineral components play an indispensable role in shale reservoirs, and the highest Barnett Shale production is associated with zones with 45% quartz and only 27% clay (Bowker 2003). The shale brittleness is correlated with the content of quartz and carbonate (Jarvie et al. 2007). Martineau (2007) suggested that different areas in the Barnett Shale contain different amounts of siliceous, carbonate and clay minerals, resulting in different fracture characteristics. Considering these aspects, Bowker (2007) highlighted that the Barnett Shale is associated with high shale gas yields owing to the high brittleness. The high brittleness allows the material to be effectively fractured hydraulically, and without these mineral fraction characteristics, shale gas extraction from the Barnett Shale would not be successful using the existing extraction techniques.

(3) Petrological characteristics of other shale formations

Other shale gas formations in North America have been extensively investigated in recent years. According to the research on petrological characteristics, the petrology of these formations is similar to those of the Barnett Shale, albeit with certain differences. For example, the Bossier gas-bearing shale reservoir in Western Texas is a mixture of shale, sandstone and siltstone (Jarvie et al. 2007). Hemmesch et al. (2014) identified seven lithofacies for the Woodford organic-rich shale: shale, phosphate nodule-bearing shale, dolomite, chert layer, radiolarian-bearing calcareous laminae, biotite-bearing mudstone and siliceous rock. The bulk mineralogy of Devonian–Mississippian black shales in the Western Canada sedimentary basin is dominated by biogenic quartz, which accounts for 58–93% of the bulk rock. The low siliceous content is attributable to the high content of carbonate minerals, and the clay minerals are mainly illite, with a small amount of unevenly distributed kaolinite (Ross and Bustin 2008). Most researchers have reported consistent results regarding the origin of silica in siliceous shales in North America (Bowker 2003; Loucks and Ruppel 2007; Ross and Bustin 2007). Similar to the Mississippi Barnett Shale in the Fort Worth Basin, other organic-rich shales in North America consist primarily of brittle minerals, with clay mineral contents lower than 50%. The clay mineral content of the well-known Green River Shale in the Uinta Basin is lower than 10%; the Heather Shale in the North Sea contains 53–57% quartz and exhibits a clay mineral content lower than 5% (Hunt 1996). By analyzing the clay minerals, organic matter content, thermal maturity, humidity and pore structure of the Fayetteville Shale, Bai et al. (2013) concluded that the relative proportions of quartz–carbonate–clay minerals influenced the physical properties of the rock, and the rock composition was the most fundamental factor affecting the effectiveness of drilling and hydraulic fracturing.

In general, the gas-bearing shale in North America is mainly composed of organic-rich siliceous shale, with a small amount of calcium, low clay mineral content and a large number of biogenic clasts. Influenced by the biological activity, the source of silica is predominantly biogenic, and it rarely has a terrigenous origin.

4. Organic matter characteristics of North American shales

The gas-bearing shales in North America are important hydrocarbon source rocks. Curtis (2002) compared the geological and geochemical characteristics of shale formations in the five major basins in North America, including the vitrinite reflectance, organic carbon content, favorable shale thickness and adsorbed gas volume. In particular, the organic carbon content of the Barnett Shale ranges from 2.0 to 7.0%, with an average of 4.5%. The organic carbon content of the Antrim Shale and the New Albany Shale is slightly more than 20%, while the Ohio and Lewis Shales exhibit lower organic carbon contents, mostly < 5%. The adsorbed gas content for the Antrim shale and New Albany shale ranges from a 13% to 70%. The genesis of shale formation in the major shale-gas-producing basins in the USA has biogenic, thermogenic and mixed origins, i.e., low thermal maturity shale (e.g., Antrim Shale with $R_o$ = 0.4–0.6%), high thermal maturity shale (e.g., Barnett Shale with $Ro$ = 1.0–2.1%) and mixed high-low thermal maturity shale (e.g., Ohio Shale with $Ro$ = 0.4–1.3% and New Albany Shale with $R_o$ = –1.3%). Moreover, the kerogen type is predominantly type I–$II_1$ (Curtis 2002; Montgomery et al. 2005). The Devonian–Mississippian strata of the Western Canada Basin exhibit a TOC between 0.95.% and 7% (Ross and Bustin 2008). The Woodford Shale in Oklahoma, USA, has a high organic carbon content of 5.01–14.81%, and the organic matter is predominantly type II (Romero and Philp 2012).

Notably, the organic matter content and thermal maturity vary considerably in different shale gas basins. Current shale gas exploration practices in the USA show that the shale maturity is generally greater than 1.3% in shale-gas-producing areas (Martineau 2007; Pollastro et al. 2007), with a maximum maturity of 4.0% in Southern West Virginia in the Appalachian Basin. Moreover, shale gas is produced only in areas with high maturity levels. The maturity of organic matter in shale reservoirs does not considerably influence the shale gas accumulation, although a higher maturity is favorable for shale gas accumulation (Jiang et al. 2010). In addition, clay minerals are hydrophilic, while organic matter is methanophilic (Zhang et al. 2012b). Therefore, the organic matter content considerably influences the shale gas sorption capacity (Chalmers and Bustin 2008a, 2008b).

5. Characteristics of shale gas reservoirs in North America

The pores in shales, which appear to be singular are isolated, are in fact connected by straight and narrow throats, and the pores are characterized by complex internal structures and porous complexes. The porosity of organic-rich shales in the five major shale gas basins in the USA is typically more than 5%, and the New Albany Shale has a porosity higher than 10% and a low permeability (Curtis 2002). The pores in organic shales can be classified as microporous (pore size up to 2 nm), mesoporous (pore size 2–50 nm) and macroporous (pore size greater than 50 nm) (Chalmers and Bustin 2008a, 2008b; Ross and Bustin 2009). The adsorption capacity of shale is also associated with micropores (Ross and Bustin 2009). The micropores in the Barnett Shale include intragranular, intergranular and intergranular micropores of authigenic minerals. The dominant type pertains to intergranular micropores formed by hydrocarbon generation evolution, clay mineral transformation, fossil silicification and framboidal pyrite formation (Loucks et al. 2009; Ross and Bustin 2009).

Research on shale reservoirs is largely dependent on advanced analytical techniques, with scanning electron microscopy, backscattering and two-dimensional (2D) and 3D imaging techniques being widely used. For example, Slatt et al. (2011) used polarized light microscopy and scanning electron microscopy (SEM) to investigate the pore characteristics of favorable formations of the Barnett and Woodford shale gas systems in North America, distinguishing several types of pores: porous floccules, organoporosity, intraparticle pores and microfractures. Curtis et al. (2012) used focused ion beam techniques combined with backscattering or SEM to observe shale gas core samples from different horizons in nine regions of North America and determined the 3D digital features of the corresponding SEM images to visualize the pore size distribution, pore structure characteristics, connectivity and coexisting minerals. The researchers indicated that pores sized approximately 3 to 6 nm have the highest number but contribute less to the total pore volume than micro- to mesopores, indicating that shale gas reservoirs are dominated by micropores and mesopores with a low porosity. Clarkson et al. (2013) investigated the pore structure of North American shale gas reservoirs by applying small-angle and ultrasmall-angle angle neutron scattering techniques combined with low-pressure adsorption and high-pressure mercury intrusion techniques and concluded that the porosity was determined by the pore size.

Various types of pores exist in shale gas reservoirs, and the evolutionary process is extremely complex due to the combined influence of diagenesis and hydrocarbon generation. Chalmers et al. (2012) comprehensively evaluated the development characteristics of pores in shale reservoirs through physical, organic geochemical and compositional analyses of shale gas favorable formation samples from different regions of North America. The researchers highlighted that the porosity was related to the pore size, the micropores contributed the least to the porosity, and the pore evolution was characterized by an increase in the number of micropores and a decrease in the number of mesopores and macropores as the porosity decreased. Moreover, the researchers clarified the relationships among the distribution characteristics of the porosity and pore size versus the content, type and evolution degree of organic matter and mineral compositions. Notably, the mesopores and macropores are mainly intercrystalline pores, intergranular pores or organic matter pores and do not follow the direction of shale laminae. The pore size is inversely proportional to the specific surface area (Beliveau and Honey 1993). Because the micropores occupy a higher specific surface area than mesopores and the smallest specific surface area pertains to macropores, the porosity decreases with the increase in the number of micropores and decrease in the number of mesopores and macropores. Pores develop during the thermal maturation of kerogen and generation of hydrocarbons (Jarvie et al. 2007). As kerogen matures, the porosity of the micropores increases (Chalmers and Bustin 2008a; Ross and Bustin 2009). Because mesopores and micropores are the main constituents of shale pore space, they are of economic importance for shale gas (Keller et al. 2011), which exists in the form of adsorbed gas. The macropores in the Barnett Shale are mainly derived from the thermal degradation of kerogen, in which kerogen undergoes thermal cracking, leading to petroleum generation (Jarvie et al. 2007; Chalmers and Bustin 2007; Loucks et al. 2009; Modiaca and Lapierre 2012; Mastalerz et al. 2013). Mastalerz et al. (2013) studied the evolution of the pores during diagenesis of the New Albany Shale by analyzing the organic matter, mineral composition and physical and gas-bearing properties of the shale. The researchers reported that the pores did not follow a constant trend during the diagenetic process. Nevertheless, with the generation of hydrocarbons, the porosity exhibited several minima and fluctuations. As the maturity increased, the porosity and total pore volume varied with the pore size distributions and pore types. Thus, the variation in the porosity is considerably influenced by the hydrocarbon generation of kerogen and organic matter transformation due to hydrocarbon migration.

Jarvie (1991) noted that the pore-space changes in organic-rich shales occurred owing to the transformation of organic matter during hydrocarbon generation. Peters (1986) suggested that during early diagenesis (*R*o of 0.6%), up to 0.6 wt% hydrocarbons were transformed by the kerogen, while in middle diagenesis, the porosity decreased with the increasing maturity of the organic matter. During the late maturation stage, the number of available open pores decreased, and the fluid flow was restricted as the early pores filled with oil or solid bitumen. The size of the pore throat was noted to be closely related to the rock porosity and permeability (Nelson and Batzle 2006), and Jarvie et al. (2007) suggested that the blocking of the roaring channels by asphaltene residues led to the low permeability. As the thermal evolution progressed, the porosity increased with the conversion of oil and bitumen to dry gas, which created microfractures and allowed the formerly closed pore system to open.

In conclusion, North American shale gas reservoirs contain mostly micropores to mesopores exhibit a high porosity and low permeability, and the macropores are not developed. The porosity is related to the type of pore, i.e., the size of the pores determines the porosity. The generation of and variation in the pores are mainly associated with the diagenesis, hydrocarbon generation and evolution of organic matter.

6. Research on diagenesis

The study of diagenesis is significance for the porosity and permeability analysis of conventional reservoirs, comprehensive evaluation of reservoirs and reservoir and gas production prediction (Yang et al. 2012). For shale gas, diagenesis controls not only the thermal evolution degree of organic matter, but also the mineral composition of shale, especially the composition of clay minerals. Additionally, the intensity of diagenesis considerably influences the development of reservoir space (Liang et al. 2012). Diagenesis influences the mechanical properties of shale, with compaction transforming loose and soft clays to mudstones and shales and cementation of minerals such as carbonates and quartz causing a shift in the mechanical properties from plastic to brittle sedimentary rocks (Bjørlykke and Karre 1997). Research on shale gas diagenesis has gradually attracted attention. Laughrey et al. (2011) comprehensively analyzed the diagenetic history of the Marcellus Formation in the Sullivan area of Pennsylvania and indicated that when the sediments of the Marcellus Formation were buried at a depth of approximately 500 m, early diagenesis was associated with mechanical compaction and mudstone dewatering. As the buried depth increased, the chemical compaction corresponded to quartz cementation and transformation of clay minerals. The organic pores developed significantly during late catagenesis, and this process continued in the metagenesis state at depths greater than 8 km. Milliken et al. (2012) analyzed the porosity, permeability and TOC of Barnett Shale samples with high maturity (*R*o: 1.52–2.15%) in the eastern Fort Worth Basin and noted that the reservoir factors were not correlated with the composition and structural characteristics of the rock due to diagenesis. Compaction and cementation caused the loss of most of the primary intergranular pores. Most of the pores were thus secondary pores filled with asphaltenes and the clastic particles were replaced.

Notably, shale gas reservoirs, as hydrocarbon-producing layers, are subject to both organic and inorganic modifications during burial and diagenesis, and the formation process is complicated. Therefore, the existing studies on shale gas diagenesis are not sufficient, and a comprehensive detailed and systematic study of the diagenesis and diagenetic evolution of shale gas reservoirs and their impact on the reservoir storage space must be conducted. Because shale-gas-bearing shales are both source rocks and reservoirs in hydrocarbon systems, the rock types are mainly muddy shales with high clay mineral contents. The diagenesis of these rocks can be examined using the research methods of hydrocarbon source rocks. For example, in hydrocarbon source rocks, the clay mineral assemblage and diagenetic evolution are clearly influenced by the acidity and alkalinity of the formation fluids and fluid composition (Niu et al. 2000).

7. Characteristics and evaluation of shale gas reservoirs in North America

From a petroleum geological viewpoint, a large amount of natural gas is generated from source rocks through a series of geological conditions and discharged in large quantities under continuous pressure. These gas migrates to permeable strata such as sandstones and carbonate rocks and accumulates in structural or lithologic gas reservoirs. The part remaining in the fine-grained sedimentary rock system forms the shale gas resources (Tian et al. 2005). This model of the generation and storage of shale gas simplifies the reservoir accumulation process and integrates the gas reservoir characteristic analysis and reservoir evaluation. This comprehensive analysis process is different from that of evaluating conventional oil and gas reservoirs.

Shale gas reservoirs in North America are large-scale continuous accumulations and exist in three states: adsorbed gas, dissolved gas and free gas, with most of the gas corresponding to adsorbed and free gas. Shale is derived from biogenic, thermogenic and mixed types of sources, with thermogenic sources being dominant (Du et al. 2011; Xiao et al. 2013). The same set of shale horizons in the same basin, affected by different stages of thermal evolution, exhibit different types of gas reservoirs. For example, the Woodford Shale in the Late Devonian-Early Mississippian of Oklahoma, USA, exhibits different types of biogenic gas and thermogenic gas reservoirs in different stages of thermal evolution of organic matter in different areas (Cardott 2012). Thermogenic shale gas reservoirs are mainly controlled by the thermal maturity of shale, while the main controlling factors for biogenic shale gas reservoirs are the formation water salinity and level of fracturing (Li et al. 2009d).

The analysis and evaluation of shale gas reservoirs, as comprehensive research tools for the exploration and development of shale gas resources, have been performed for each shale gas basin and formation. For example, Ross and Bustin (2007) analyzed the shale gas potential by studying the organic matter content, organic matter maturity and gas-bearing properties of the Early Jurassic Gordondale mudstone in the Peace River region in Northeastern British Columbia, Canada. Bowker (2007) studied the type, thermal evolution and conversion characteristics of organic matter, combined with the adsorbed gas volume and mineral composition of shale and analyzed the shale gas system. Ross and Bustin (2008) comprehensively analyzed the shale gas potential by performing stratigraphic and tectonic studies of the Devonian–Mississippian system in the Western Canada Basin, examining the organic matter and mineral composition and investigating the gas-bearing properties. Chalmers and Bustin (2012b) examined the shale gas potential of the Cretaceous Shaftesbury Formation in Northeastern British Columbia, Canada through organic geochemistry, mineralogy, porosity, and gas content analyses and concluded that the present burial and organic matter maturity of shale formations influences the hydrocarbon generation capacity more notably than the TOC content. The United States Geological Survey (USGS) identified the Lower Cretaceous Pearsall Formation in Southern Texas as a potential shale gas resources through hydrocarbon investigations of the Mesozoic strata in the Northern Gulf Coast. Moreover, Hackley (2012) verified the potential of shale gas reservoirs by analyzing the lithology, stratigraphy and depositional environment of the Pearsall Formation.

The examples of shale gas development in North America demonstrate that shale gas reservoirs are dominated by adsorbed gas, and the shale adsorption capacity determines the amount of adsorbed gas. The adsorption capacity of shale is related to factors such as the mineral composition, organic matter content, kerogen type, formation water content, pore size and structural characteristics and thermal evolution stage of the organic matter. Organic-rich shale with a higher organic matter content, higher thermal evolution level, and lower formation water content corresponds to higher adsorbed gas volumes (Ross and Bustin 2007, 2009; Hao et al. 2013). The effect of the mineral composition on the gas adsorption can be observed by the fact that quartz and carbonate minerals have lower internal surface areas and therefore adsorb a lower amount of gas (Ross and Bustin 2007). Ross and Bustin (2009) reported that in dry conditions, illite and smectite exhibit higher gas adsorption capacities than kaolinite. Schettler and Parmoly (1990) indicated that the main adsorption space in the Devonian shale of the Appalachian Basin is provided by illite, and the contribution of the kerogen to the adsorption space is less significant. Zhang et al. (2012b) noted that in organic-rich shale, the adsorption capacity of the minerals is lower than that of organic matter. Hill et al. (2007b) analyzed the Barnett Shale in the Fort Worth Basin and concluded that the volume of shale gas is related to the organic matter content, thickness and maturity of the shale.

Overall, in shales with a low matrix porosity, the gas-bearing properties and microfracture development characteristics influence the shale gas production capacity (Curtis 2002). The gas-bearing property of shale gas is related to the content and type of organic matter, level of thermal evolution, rock type, mineral composition and physical properties. In fact, the rock mineral composition and organic matter characteristics are the basis of shale gas development. The level of organic matter thermal evolution determines the type of shale gas reservoir and storage space. The mineral composition, organic carbon content and organic matter maturity of shale rocks are the three most important factors for shale reservoir development (Curtis 2002; Jarvie et al. 2005). Therefore, the evaluation of shale gas reservoirs, analysis of shale gas deposits and prediction of potential resources are based on the fundamental understanding and evaluation of shale gas in terms of the petrography, rock composition, organic matter type and maturity and reservoir properties. The diagenesis and original components of shale must be considered when evaluating reservoirs (Ross and Bustin 2007).

While fractures are necessary to ensure high gas production in the Barnett Shale, the macroscopic fractures do not considerably influence the hydraulic fracturing as they are filled with carbonate minerals (Bowker 2003). In the Barnett shale, most of which is a closed system, the organic and inorganic gases produced by hydrocarbon evolution are not immediately released, leading to the generation of high pressures (Jarvie et al. 2007). Gaarenstroom et al. (1993) estimated the oil and gas cracking capacities and suggested that the pressure generated by 1% oil cracking in a closed system could attain the threshold for rock cracking. This finding suggests that the microfractures and migration channels in the Barnett shale are at least partially derived from the generation of early hydrocarbon and nonhydrocarbon gases and from the secondary cracking process of hydrocarbons after oil and gas are generated. Bowker (2007) found that although Newark East has been the largest natural gas field in the Fort Worth Basin since 2001, due to the development characteristics of the facture system, the gas production in different areas of the Fort Worth Basin varies considerably. The Barnett Shale exhibits low gas production near faults and folds, and the structural fractures determine the gas production of the Barnett shale.

Montgomery et al. (2005) believed that the development of shale gas must be based on a comprehensive study of the geological characteristics, geochemical analyses and technological developments. The geological characteristics can be examined to clarify the characteristics of shale reservoirs, and geochemical analyses can clarify the potential productivity of shale and formation pattern of shale gas. After the reservoir and resource potential have been determined, the technological developments determine the productivity of shale. Therefore, the analysis of the geological characteristics and geochemistry of shale gas reservoirs based on the latest hydraulic fracturing and horizontal well technologies is a fundamental and decisive part of shale gas exploration and development, and the study of its sedimentological, petrological and diagenetic effects and organic geochemical aspects eventually determines the effectiveness of shale gas reservoir development.

According to the shale gas production practices of the USA, the favorable reservoir characteristics of thermogenic shale gas can be summarized as follows: TOC $\geq$ 2%, shale thickness $\geq$ 15 m, $1.1\% < Ro < 3\%$ and quartz content $\geq$ 28% (Li et al. 2009d). Shale gas reservoirs with high production and economic benefits correspond to a wide distribution area, moderate burial depth, large thickness (>30 m), organic matter abundance (TOC $\geq$ 2%), kerogen type I or $II_1$, moderate maturity ($1.1\% < Ro < 2.5\%$), high gas content (3–10 $m^3$/t), low water production, moderate clay content (<40%), high brittleness (i.e., low Poisson's ratio and high Young's modulus) and surrounding rock, as these aspects facilitate hydraulic fracturing control (both the upper and lower strata are limestones) (Curtis 2002; Montgomery et al. 2005; Pollastro et al. 2007; Li et al. 2009d). Diverse reservoir rock types, dominant free gas, well-developed caprocks and overpressure reservoirs are also characteristics of high-production shale (Xiao et al. 2013). Curtis (2002) compared the geological and geochemical characteristics of shale gas, such as the vitrinite reflectance, organic matter content, favorable shale thickness and adsorbed gas volume, of favorable shale gas strata in five major basins in North America and concluded that the factors affecting shale gas production rates can compensate for one another.

### 1.1.2 Research History and Status of Shale Gas in China

China is the third country initial to shale gas exploration, which is later than the USA and Canada. The resource of shale gas is rich in China, which is approximately equal to it in the USA (Zhang et al. 2009). It is no doubt that the shale gas will be the new growth point of natural gas in China (Ye and Zeng 2008). The shale gas has been entered into the commercial stage in China since the industrial shale gas flow had been gotten in the well JY-1 in 2012. Although the annual output of shale gas is gradually rapid growth, the shale gas is mainly coming from the middle-shallow burial depth layer (1000–3000 m in depth) in China. There is a big gap between the annual output of shale gas in China and USA (Zhang et al. 2021). In present, the breakthrough of shale gas has been gotten in the marine shale gas in the Southern China; however, there are a few of questions and challenges in the shale gas industry in China now. The enrichment condition of the shale gas has not been well understood (Jiang et al. 2020).

Since the 1960s, the industrial gas flow has been intermittently observed in the fractured shale reservoirs in different basins. However, it has not been paid enough attention. The preliminary research on shale gas resources was started in 2004 by the Strategic Research Center of Oil and Gas Resources, Ministry of Land and Resources, China (SRCOGR, which is presently known as the Ministry of Natural Resources) and China University of Geosciences (Beijing), which was the first time focused on the shale gas in China. Since 2006, the shale gas exploration has been started in China symbolized by the project "The potential evaluation and favorable area prediction for shale gas resource in the key areas of China". This project is belonged to the national major project named "The strategic survey of oil and gas resources and favorable area prediction" which is carried out by the institutes organized by the SRCOGR, such as, China National Petroleum Corporation (CNPC), Sinopec Corporation (SPC), Chengdu Center of Geological Survey, Chongqing Coal Geology Research Institute. The shale gas in China was assessed by dividing the China into five evaluation units, such as the Upper Yangtze and Yunnan-Guizhou-Guangxi unit, Middle-lower Yangtze and South-east unit, the north and Northeast unit, the Northwest unit and the Tibetan unit. Five pilot areas were set up as the Sichuan–Chongqing–Guizhou–Hubei pilot area for shale gas, the Qijiagulong depression in Songliao basin pilot area for shale gas and oil shale, the shale gas-tied gas-coalbed methane pilot area in the Northern Qinshui basin, the lower Yangtze and Anhui-Zhejiang pilot area for shale gas. Several key blocks were selected out too. The companies major in the shale gas exploration were set up by the CNPC, SPC, China National Offshore Oil Corporation (CNOOC), which symbolizes the beginning of shale gas exploration in China. Meanwhile, the industrial shale gas flow was gotten in some local areas. Furthermore, the shale gas research teams were gradually established in research institutions and private enterprises too. In present, the disciplines boom has been formed in shale gas exploration. The formal shale gas field development was kicked off with the setting up of Fuling shale gas field, in July 2014.

According to the Resource evaluation results of the Ministry of Natural Resources, PRC (formerly Ministry of Land and Resources) in 2015, the shale gas resource is about $121.86 \times 10^{12}$ $m^3$ in China. The recoverable resources of shale gas are $21.81 \times 10^{12}$ $m^3$. The marine shale gas is $13.00 \times 10^{12}$ $m^3$, mainly enrichment in the Sinian, Cambrian, Silurian Formation and so on, in the Upper Yangtze area and Western Tarim basin. The terrestrial shale gas is $3.73 \times 10^{12}$ $m^3$ which is enrichment in the Ziliujing Formation in Sichuan Basin, the Yanchang Formation in Ordos basin, the Shahejie Formation in Bohai Bay Basin and the Qingshankou Formation in Songliao basin. $5.08 \times 10^{12}$ $m^3$ is enrichment in the marine and continental transitional facies shale, such as the Permian Formation in the middle-Upper Yangtze, the Carboniferous–Permian Formation in the Ordos basin, Junggar Basin, Tarim Basin and so on (Sun et al. 2020). During the 2016–2020, the shale gas has entered in the rapid development stage. A lot of the innovation and breakthrough were gotten in this period. In present, the shale gas has been seeming as an important field for increasing natural gas storage and production in China (Zhao et al. 2019). The shale gas development has been accelerated by CNPC. The production capacity construction has carried out in the shallow shale gas resources (<3500 m in depth) in Changning, Weiyuan and Zhaotong. Up to the end of 2019, the accumulative proved shale gas geological reserves have been $10{,}610 \times 10^8$ $m^3$. The annual output of CNPC is $80.3 \times 10^8$ $m^3$ and $116.1 \times 10^8$ $m^3$ in 2019 and 2020, respectively. The marine shale gas in Wufeng-Longmaxi Formation has been economically exploited by the Sinopec, in the Fuling area and Weirong area. The accumulative proven shale gas geological reserves amounted to $7255 \times 10^8$ $m^3$ at the end of 2019. The annual outputs of SINOPEC were $73.4 \times 10^8$ $m^3$ and $84.1 \times 10^8$ $m^3$ in 2019 and 2020, respectively (Zou et al. 2021). The Sinopec reported that the accumulative proven shale gas geological reserves were $9408 \times 10^8$ $m^3$, at the end of 2020. The favorable area for shale gas is mainly distributed in Sichuan Basin and its surrounding area (Cai et al. 2021). It is deduced that the annual output of shale gas in China will be $300 \times 10^8$ $m^3$ in 2025, and likely will be $350 \times 10^8$ $m^3$–$400 \times 10^8$ $m^3$ in 2030. The shale gas will occupy a major proportion in the increasing of gas in China. The major contributor will be the marine shale gas from the deeper shale strata. The annual output of the marine shale gas likely be $150 \times 10^8$ $m^3$–$200 \times 110^8$ $m^3$ in 2030. The shale gas exploitation in Sichuan Basin will accelerate the Sichuan–Chongqing area as the biggest oil and gas production area in China. The Sichuan Basin will be constructed as the "Daqing gas field" (Zou et al. 2021).

The shale gas in China is characterized with different enrichment types, wide distribution and with huge potential. Shale strata were well deposited in the strata of different ages. The shale strata are deposited in various environment, such as the marine, terrestrial and the transitional facies. The organic-rich shale is commonly act as the source rock in the petroliferous basin. The Paleozoic shale in Sichuan Basin is mainly marine sedimentary, with stable regional distribution, large thickness, organic matter enriched and high thermal evolution. A large amount of oil and gas has been observed in Paleozoic shale which is a realizable field for shale gas exploration and development (Zou et al. 2010a). The Paleozoic shale in Southern China has experienced a complex tectonic evolution. It is with the similar geological conditions and tectonic evolution characteristics to the typical shale gas basins in eastern USA (Long et al. 2009). Paleozoic shale gas is an important field to the exploration and production of shale gas in China.

At the beginning of shale gas study, the scholars were focus on the enrichment mechanism (Zhang et al. 2003, 2004), the accumulation condition (Zhang et al. 2008a; Chen et al. 2009a; Wang et al. 2009a, b, c, Nie et al. 2009a), the evaluation of favorable area (Zhang et al. 2008b; Zhao et al. 2008; Cheng and Pi 2009; Pan and Huang 2009; Li et al. 2009d) and so on. The research degree is relatively high in the middle-large petroliferous basin (Zhang et al. 2008; Wang et al. 2009a; Huang, 2009b). The study is the most advanced in the marine shale in south China. Based on the enrichment mechanism study and the comparison of geological conditions of shale gas in China and the USA, Zhang et al. (2009) concluded that the geological conditions are superior in China for shale gas, with the same shale gas potential as the USA. The Shale gas in China is characterized by high abundance of organic matter, high thermal evolution and stronger post-renovation. Meanwhile, the shale gas is characterized by coexistence of marine and continental facies, dominated by the sedimentary zones and complex distribution. For the absent of core samples for shale gas, most of the early studies were based on the conventional oil and gas exploration data, coalbed methane and solid mineral exploration data. The shale samples were coming from the outcrops or the shallow layer. Due to the lack of practices data, many analogies are carried out by referring to foreign materials such as the USA (Xu and Bao 2009, Nie et al. 2009a, Zhang et al. 2004; Zeng et al. 2011; Chen et al. 2011a). Meanwhile, to a certain degree, the progress of the shale gas industry is restricted by the deficiency of the shale gas exploration theories and methods (Li and Zhao 2009). Basing on the geological characteristics and accumulation conditions of Shale gas in China, Li et al. (2012c) concluded that Marine shale gas exploration prospect in China is the best and Sichuan Basin and its surrounding areas are the most realistic. It needs to be verified the potential of shale gas in the marine and continental transitional shale and coal measure shale. Lacustrine shale gas is mainly distributed in the central area of the depression and with a certain exploration potential. In conclusion, in the early stage of shale gas research in China, a side range of interests was focused on the marine shale gas in the middle and Upper Yangtze area. And, the research degree of it is most advanced in China. Since 2009, great progress has been gotten in the shale gas industry in Southern China. The key factors for the trap and enrichment of Chinese-style shale gas are concluded, such as, the shale gas favorable area is dominated by the "sedimentary facies and preservation conditions", the sweet-spot areas are dominated by the "Tectonic types and tectonic processes" (Guo 2016).

The study area of this book is the Southern Sichuan Basin and its surrounding area. The target layer is the Ordovician Wufeng Formation-Silurian Longmaxi Formation. Hence, this work is basing on the modern research of marine shale gas in Southern China, mainly involving Ordovician Wufeng-Silurian Longmaxi Formation and part of Cambrian Niutiantang/Qiongzhusi Formation in Paleozoic.

1. The geological setting of the shale gas in Southern China

There are three regional source rock layers in Paleozoic in south China. The excellent source rock is characterized with the siliceous-shale and the dark shale in the Lower Cambrian Niutiantang (or Qiongzhusi) Formations, the Upper Ordovician Wufeng Formation to Lower Silurian Longmaxi Formation. The high-quality source rocks are mainly argillaceous and siliceous rocks in the Upper Permian Longtan Formation or Wujiaping Formation and Dalong Formation. The organic-poor limestone is non-source rock or poor source rocks (Fu et al. 2011). Similar to shale gas in north America, favorable shale gas formations in China are deposited in the deep-water platform located at the foredeep belt (or depression zone) in the early foreland basin, (Chen et al. 2011a). The Yangtze platform has been in the stage of consecutive thermal deposition since the late Sinian. The structural pattern is characterized with "two basins separated by one platform" in the early Paleozoic. The shale was mainly deposited in the depression and slope of platform margin. The shale mainly deposited in the intraplatform depressions and platform margins, with the restriction of the geographical pattern of passive continental margin during the lower Cambrian Niutiitang Formation depositional period. The shale is characterized the thinner thickness and high organic matter content in the deep-water environment and thicker thickness and low organic matter content in the shallow-water environment. In late Ordovician to early Silurian, the south China plate initial converged with the Yangtze plate. The shale in Wufeng-Longmaxi Formations is deposited in the plate convergence in the early formation of depression. In the depression, the shale is characterized with thicker thickness, high organic matter content. The organic-rich shale is relatively thinner at the outside of the depression (Chen et al. 2011a; Liang et al. 2009).

The evolution of the middle-Upper Yangtze region began with the breakup of Rodinia continent in Nanhua Period. From Sinian to Early Ordovician, the whole middle and Upper Yangtze region was in the background of extension and splitting. A stable middle-Upper Yangtze craton basin was formed within the continental block (Zeng et al. 2011). There is a difference in the spatial and temporal distribution of the Sinian-Silurian cratonic basin in the middle-Upper Yangtze basin. It has undergone two stages from extension to compression, with the evolution process ordinally from rift basin to fissure basin and depression basin. The first stage is from Sinian to early Ordovician. It is characterized by the evolution from early rift to fissure basin in the extensional environment, and the formation is mainly carbonate. The II stage is from late Ordovician to early Silurian. The study area underwent an extrusion stress environment. The basin is a successional compressional depression basin within the craton. The craton margin is generally extruded and uplifted. As a whole, the basin pattern is restricted by uplift segmentation. The sedimentary formations are mainly clastic and mixed type. The lithological association is characterized with the carbonate is gradually drop, the clastic rocks is gradually increasing in the upward (Huang et al. 2011a).

Basing on the outcrops, well test, core samples and the tests of sedimentology, geochemistry, reservoir engineering, Dong et al. (2010) concluded that the distribution of organic-rich black shale in Qiongzhusi and Wufeng-Longmaxi Formations were dominated by the neritic facies to deep shelf sedimentary environment during the Early Paleozoic in the Upper Yangtze Area. The lower Paleozoic formation is the favorable layer for the shale gas. The organic-rich shale in Longmaxi Formation was deposited during the transgressive systems in Early Silurian (Chen et al. 2009a, Huang et al. 2011a, Li et al 2012c). Meanwhile, the organic-rich shale is deposited in the area with slow regressive system, where is favorable to the shale gas formation. Then the sea level began to decline slowly and entered the high stand systems tract, which was mainly semi-deep water shelf deposition. The sandy content is gradually increased with the increasing of silty shale, argillaceous siltstone and siltstone in upward, which composed the regressive sedimentary sequence.

2. Petrological characteristics

(1) Lithofacies and mineral composition

There is a huge difference between different scholars on the lithofacies division of the Longmaxi Formation in Sichuan Basin and its surrounding area. The petrology has rapidly developed in the last ten years, with a lot of study on the lithofacies (sedimentary microfacies) had been carried out. There are many lithofacies division schemes. It can be roughly divided into three types as following,

(1) The lithofacies are classified mainly according to the mineral composition, assisted with the sedimentary structure. However, no unified standard has been established. For example, one division scheme is proposed by Zeng et al. (2011), which divided the Longmaxi Formation into three lithofacies, such as the carbonaceous shale facies, silty shale facies, marl facies. Liang et al. 2012 proposed that there are five lithofacies in Longmaxi Formation, which is carbonaceous shale, siliceous shale, silty shale, calcareous shale, ordinary shale. Zhang et al. (2012b) concluded that the Longmaxi shale is composed by black, gray-black and dark gray calcareous and siliceous shales, sandy shales or thin siltstones. The laminated structures are commonly observed in the Longmaxi shale. Wang et al. (2014b) proposed that there are eight lithofacies in Longmaxi Formation, which is siliceous shale, calcium siliceous shale, micritic calcareous shale, calcareous laminate shale, shell marl, wavy bedding shale, dolomitic shale, phosphorus shale. Zhao et al. (2016) proposed that Longmaxi shale is composed by the siliceous shales, clayey shales, silty shales, calcareous shales, core-bearing argillaceous limestone/calcareous mudstone, siltstone-fine sandstone and bentonite. Another classification scheme is proposed by Wu et al. (2016). Basing on siliceous mineral (quartz and feldspar), carbonate minerals (calcite and dolomite) three mineral and clay mineral, it can divide the shale into siliceous shale, calcareous shale, clay shale and mixed type of shale. The shale can be classified into more than 30 types according to the contents of the three components.
(2) The shale can be classified in different types, according to TOC content and mineral composition. Jiang et al. (2016) classified the Longmaxi shale in Weiyuan area into 11 types, for example the organic-rich siliceous shale facies and organic-rich carbonate-siliceous shale and so on.
(3) The shale was divided into different types, according to the laminar and mineral composition characteristics too. Firstly, Liu et al. (2011) divided the Wufeng-Longmaxi shale in east Sichuan Basin into eight lithofacies, including the stratified-non-stratified mud/shale dolomitic siltstone, stratified calcareous mud/shale argillaceous siltstone, stratified-non-stratified silty mud/shale, silty-fine-grained sandstone, calcareous nodules, organic-rich shale without lamellation. The mineral mainly composed by quartz or carbonate. This method was optimized by Ran et al. (2016) by taking the silica content into account. The Longmaxi shale can be divided into 9 types, such as the silicon-poor non-parallel laminated shale, silicon-rich parallel laminated shale. Basing on the core samples observation and thin sections identification of Well CX-1, Chen et al. (2013a, b) divide the Longmaxi shale into lamellar shale, lamellar calcareous shale, lamellar dolomitic shale, lamellar carbonate shale and lamellar silty shale. The lamellar is composed by the mud grade of quartz, feldspar, clay, organic matter, silt grade of quartz, feldspar, metasomatic origin of calcite, dolomite and pyrite (local, small) content varies.
(4) Recently, Shen et al. (2021) classified the Wufeng-Longmaxi Formation into four types of shale facies combinations, based on the comprehensive consideration of mineral composition, reservoir physical properties, bedding fractures and the influence of bedding on fracture network formation. This scheme is focused on the fracturing ability of shale gas reservoir to form fracture network. According to hydrodynamic genesis of shale deposition, eight lithofacies shale has been classified into strong and weak hydrodynamic zones by Wang et al. (2014b). And, he pointed out that siliceous shale, calcium-bearing siliceous shale and micritic calc shale under the weak hydrodynamic zone have higher organic carbon content. On the other hand, scholars have also done some research on the lithofacies of Guanyinqiao Formation. Liang et al. (2022) divided the Guanyinqiao lithofacies according to the biological characteristics of the Guanyinqiao Formation. Wang et al. (2016) had discussed the significance of mineral composition and distribution characteristics for shale gas exploration. By referring to the lithofacies division scheme of Wufeng-Longmaxi Formation by Wu et al. (2016), Wei (2020) classified the lower Cambrian shale in Western Hubei into four main lithofacies combinations according to the three-end element of siliceous minerals (quartz + feldspar), carbonate minerals and clay minerals. The shale facies are mainly silica-clay-bearing shale facies, ash/silica mixed shale facies, clay/silica mixed shale facies and

argy-rich/ash-mixed shale facies. The organic matter is enrichment in the siliceous shale, and the TOC in the clayey shale is generally smaller than 2.0%.

The mineral composition is obviously affected by the sedimentary environment. For example, the organic-rich shale deposited in the depression environment of Marine platform is generally characterized with enrich siliceous and calcareous organisms, with little or no clay minerals. Siliceous and calcareous minerals are mainly the remains or detritus of various hydrocarbon-forming organisms which have been buried and evolved through various diagenesis (Qin et al. 2010a). However, the mud shales formed in the sea–land interaction or continental lacustrine basin are usually enrich the clay minerals. The organic matter is saved in the form of organic clay mineral aggregate in shale by the adsorbed of the clay minerals (Lu et al. 1999; Cai et al. 2006, 2007; Li et al. 2006; Yu 2006). A large number of studies reported that the mineral composition of Wufeng-Longmaxi Formation is mainly quartz, followed by clay minerals, and other components also include feldspar and a small amount of carbonate minerals. Liu et al. (2015) found the mineral composition of Longmaxi Formation shale in Southeast Sichuan is quartz (avg. 36.07%), clay minerals (avg. 41.55%) and little carbonate mineral. Quartz content is the highest at the bottom and decreases upward, while clay content increases. This conclusion has been observed in the other shale gas well too, such as the well XY-1, YY-1 and the well in the Jiaoshiba area, where the Wufeng-Longmaxi shale is mainly composed by the quartz and clay minerals, with a small amount of plagioclase, potash feldspar, calcite, dolomite and pyrite (Wu et al. 2015).

The lithology of Longmaxi Formation in Sichuan Basin and its periphery is similar to that of North American shale. Both of them are mainly consisted with carbonaceous shale, siliceous shale, silty shale, and a certain amount of silty fine grained clastic rocks such as fine siltstone, argillaceous siltstone. The mineral composition is mainly quartz, with big content of organic matter, maldistribution of calcium and extensive distribution of pyrite. However, it is different from the bio-siliceous shale in North America that the quartz in the Longmaxi Formation is mainly terrigenous and relatively little diagenetic metasomatism in the study area (Zeng et al. 2011; Chen et al. 2011a ; Liu et al. 2011; Zhang et al. 2012b; Liang et al. 2012). Basing on the petrology, mineralogy and biological characteristics analysis on the marine source rock in the middle-Upper Yangtze, Qin et al. (2010a, b) and Fu et al. (2011) pointed out that the siliceous rocks were mainly biogenic. The mainly minerals of the key source rocks in south China were mainly from the benthic siliceous or calcareous frameworks after burial evolution. The source rocks are mainly biogenic in south China. The organic matter is partly saved in the siliceous and calcium minerals in the marine shale. The shape of these minerals is irregular, and with the characteristics of raw chips, multitudinous elements (especially with some little or other trace elements). There is an obviously differences in smoothness and color of the minerals surface. It is indicating that the siliceous and carbonate minerals in the organic-rich shale is not from terrigenous input (Qin et al. 2010a). Zhang et al. (2012b) found the radiolarians and siliceous sponge spicules in well YS-1, the Sanhui outcrops in south Sichuan province, the Hegou outcrops in the Shizhu county and other areas. Meanwhile, the content of animal organic debris was particularly prominent in the muddy deep water shelf environment, with the highest relative 37% and an average 14%. It likely as an important component for hydrocarbon generation. The organic-rich siliceous rocks are commonly resulted by the combined action of hydrothermal activity and biological deposition. Quartz is mainly from biological deposition and $SiO_2$ chemical precipitation caused by hot water. This may help us understand the reason that dark bedded siliceous rocks are commonly organic-rich rock, while the organic matter content is commonly very low in the flint which is merely formed by the chemical precipitation (Fu et al. 2011).

Lithology and rock mineral composition are double key internal factors for the mechanical properties of rock and even fracture feasibility (Sui et al. 2007), which are the fundamental factors affecting the pore structure of shale gas reservoir too (Chen et al. 2013). Hence, the mineral composition and brittleness index are two important indicators for the description and evaluation of organic-rich shale reservoirs in Longmaxi Formation now (Liu et al. 2012). Most of the Longmaxi Formation profiles in Sichuan Basin is characterized that the clay and carbonate minerals are increasing in the upward, while the quartz decreasing (Liang et al. 2009; Chen et al. 2011a; Liu et al. 2012). The brittleness index of the organic-rich shale is about 50–75% in the depositional center. As far from the land, the content of carbonate minerals is gradually increasing, while the terrigenous clastic minerals are gradually decreasing, in the limited shallow sea facies (Liu et al. 2012).

Furthermore, the deposition of pyrite is related to biological processes too. A lot of $H_2S$ is formed by the sulfate reacts with organic matter with the action of bacteria in the anoxia water. In the early diagenetic stage, $H_2S$ combines with iron ions to form sulfide. Then, the sulfide reacts with active functional groups in organic matter to form organic sulfur. However, metal ions are more easily combined with $H_2S$. Once the iron ions present in the environment, the formation of pyrite is prior to that of organic sulfur (Zhang et al. 2013a).

Clay mineral characteristics

Clay minerals as a general term for finely dispersed water-bearing layered silicate and water-bearing amorphous silicate minerals, which are the most abundant minerals in strata (Li et al. 2012c). The formation, transformation and disappearance of clay minerals in mudstone are influenced by many factors such as the depositional environment, diagenesis and source rock (Zhao and Chen 1988). The key factors dominated the formation of clay mineral are commonly different in different regions and layers, which resulted the difference in the distribution and types of clay mineral. It is helpful to analyze the paleoenvironment and diagenesis of clay minerals by analyzing their types, occurrence, content and variation characteristics. For a long time, clay minerals have been seemed as a favorable tool to oil and gas exploration. Sedimentary rocks are rich in montmorillonite, which is conducive to the generation and migration of oil and gas through diagenesis Daoudi et al. (2010). There is a law of co-evolution between the ratio of illite/montmix and organic matter. A lot of organic matter is adsorbed in the clay minerals, which have a strong catalytic effect on the process of hydrocarbon generation (Zhang et al. 2013a). The type and content of illite in shale are important factors and indicators for the content of hydrocarbons.

Little previous work was focused on the clay minerals about the shale gas. Basing on the analysis of clay mineral in the dark shale, Li et al. (2012c) discussed the influence of clay minerals on the reservoir property of shale. It is concluded that the composition, distribution and the formation mechanism of the clay mineral is not only showing the characters of the depositional and diagenetic environment, but also with a certain influence on the porosity and permeability. Therefore, the study on clay minerals should be emphasized in shale gas reservoir.

3. Characteristics of organic matter and its relation to mineral composition

(1) Characteristics of organic matter

There were two hydrocarbon generation centers for Longmaxi Formation in Sichuan Basin and its surrounding area, which are the Wanxian-Shizhu of hydrocarbon generation center in the eastern Sichuan Basin and the Zigong-Luzhou-Yibin hydrocarbon generation center in the Sichuan Basin (Wang et al. 2009a). The burial depth of Silurian source rocks is deeper in the eastern and Northern of Sichuan Basin than the south Sichuan Basin, while the thermal evolution of the shale is similar to each other of the two areas (Zeng et al. 2011).

The organic matter is enriched in the dark Longmaxi shale. Under a microscope, the shale is opaque black and gray black. Several different occurrence forms of organic matter are observed in the microscopic identification and electron probe analysis (Zhang et al. 2013a). The organic matter abundance is an important index for source rocks evaluation. Three conventional indexes are applied to organic matter abundance of source rocks, such as the total organic carbon (TOC), hydrocarbon generation potential ($S_1 + S_2$) and chloroform bitumen “A”. In consider of the high to over thermal evaluation of Paleozoic source rocks in Sichuan Basin, chloroform bitumen “A” and hydrocarbon generation potential can no longer be availably showing the hydrocarbon generation capacity of high-overmature source rocks. Hence, TOC has been regarded as the key index to the evaluation of hydrocarbon generation intensity in Paleozoic mud/shale in Sichuan Basin (Wu et al. 2013a). Therefore, total organic carbon content is an important index for evaluating the abundance of source rocks, as well as an important parameter to show the intensity and amount of hydrocarbon generation. According to the definition of shale gas, organic matter in shale is the parent material of hydrocarbon, as well as an important adsorption medium and carrier of shale gas (Li et al. 2007; Zhang et al. 2013a).

The Longmaxi Formation is characterized with high organic matter content and stronger hydrocarbon generation potential, which is similar to shale gas in North America. According to the TOC tests from the outcrops and core samples, the TOC is in the range of 0.35–18.40%, with an average of 2.52% in the south Sichuan Basin. In the 261 samples, the TOC is ranging from 0.50 to 8.75%, with an average of 2.53%. About 45% of them are with TOC bigger than 2%, which are mainly located at the lower Longmaxi Formation (Huang et al. 2012). Basing on the organic geochemistry analysis, Zhu et al. (2010) pointed out that the TOC is 1.2–5.6% (avg. 3.1%) in Longmaxi Formation in Sichuan Basin. In Sichuan Basin, the TOC is 5.1–6.8% (avg. 3.6%) in Wufeng shale. In the periphery of Sichuan Basin, the value of TOC in Wufeng shale is smaller than it in the Sichuan Basin, such as the TOC is 2.6–4.2% (avg. 3.2%) in well PY-1 (Zhao et al. 2016).

The kerogen in the Longmaxi shale is mainly in the type of Sapropel in Sichuan Basin. Kerogen is amorphous and derived from lower aquatic organisms (Huang et al. 2012). Kerogen was flocculent under scanning electron microscope. In organic matter, the content of algae-amorphous group is 58.9–78.3% (avg. 71.2%). The content of animal organic debris group is 7.5–26.4% (avg. 15.9%). The content of secondary group is 11.2–14.8% (avg. 12.7%) (Zhu et al. 2010). In consider the H/C and O/C ratio of rock pyrolysis analysis cannot be used to determine the kerogen type for the high thermal evolution sample, $\delta^{13}C$ values are commonly used to determine the types of organic matter in Sichuan Basin, for the carbon isotopic composition of kerogen is less affected by thermal evolution (Hao and Chen 1992; Huang et al. 1997). The $\delta^{13}C$ values of the I-$II_1$ type kerogen are ranging from −32.04 to −28.78% (avg. −30.23%) (Wang et al. 2000). According to the maceral of kerogen, Chen Wenling et al. (2013) concluded that the kerogen of the shale at the bottom of Longmaxi Formation in Well CX-1 is Type I, with the algal particles 7.7–11.2% (avg. 9.53%), carbon bitumen 2.4–6.8% (avg. 4.0%), microsomal content 4.6–9.4% (avg. 6.65%), animal body contents 2.1–11.6% (avg. 7.76%). According to the kerogen microscopic analysis of core samples in well JY-1, Guo and Liu (2013) pointed out the Longmaxi shale is the I type kerogen, with $\delta^{13}C$ (PDB) −29.2 to −29.3%. The carbon isotope of natural gas is obviously inversed, as $\delta^{13}C_1$ (PDB) is −29.2%, while $\delta^{13}C_2$ (PDB) is −34.05%. It can be concluded that kerogen is mainly the type I kerogen and partly with the $II_1$ kerogen in the Longmaxi shale in Sichuan Basin (Wang et al. 2014b; Guo et al. 2014). The gas generation potential of Longmaxi shale is better than North American shale in which the kerogen is mainly composed by the II kerogen.

The thermal evolution of the Longmaxi shale is higher than north America. The shale gas discovered in China is thermal genesis and with the similar enrichment conditions to USA. However, there are some obviously differences between China yet (Li et al. 2012c). The thermal evolution history is showing that the Longmaxi Formation in Sichuan Basin was reach the low maturity stage at the end of Early Permian (*R*o is 0.5–0.7%), reached the peak of hydrocarbon generation at the end of Triassic (*R*o is 0.9–1.1%) and entered wet gas–gas condensate stage at the end of Early Jurassic (*R*o is about 1.3%). In present, it is in the late stage of hypermaturity, and all liquid hydrocarbons are cracked into dry gas (Huang et al. 2012). It is reported that the burial depth of Longmaxi shale is distributed in a wide range, especially it is deeper than 5000 m in local area, while the $R_o$ is merely in the range of 2.2 to 4.0% (Wang et al. 2009a; Liu et al. 2009, 2016; Zhu et al. 2010; Chen et al. 2013a, b; Wang et al. 2016; Guo et al. 2014).

(2) The relationship between organic matter and mineral composition

The laboratory studies showing that there is a positive correlation between the TOC and the gas generation rate and adsorbed gas volume of shale gas (Wang et al. 2009a, 2012b). The mineral composition is one of the key factors for the total gas content of shale (Ross and Bustin 2008). Therefore, it is likely with a certain correlation between the mineral composition and organic carbon content in shale. For example, Zhang et al. (2013a) concluded that the silicification of rocks may relate to the organic matter co-existed with cryptocrystalline quartz and illite, in the late filling veinlet. A lot of organic matter is adsorbed on the clay mineral and cryptocrystalline ultrafine quartz, which catalyzes the hydrocarbon generation. Furthermore, a lot of organic matter is observed in cleavage cracks or fissures of primary minerals and secondary enlarged edges, which is indicating that multiple hydrocarbon migration may have occurred during diagenesis in this area.

The Paleozoic shale in middle-Upper Yangtze is mainly composed by the clay minerals content, brittle minerals (quartz and feldspar), carbonate minerals (calcite and dolomite) and a small amount of sulfate minerals and sulfide (Fu et al. 2011; Qin et al. 2010a, b). Basing on the clay minerals and sulfides analysis, Fu et al. (2011) point out that the source rocks deposited in different environment can be with similar abundance of organic matter but with different mineral compositions. However, basing on the systematic X-ray diffraction analysis of organic-rich shale (TOC > 1.5%) sampled from diachronous marine strata in south China, Qin et al. (2010b) pointed out that there is a certain correlation between the total organic carbon content and mineral content of marine shale in South China. There is a negative correlation between the TOC and the clay mineral content, while a positive correlation between the TOC and the content of quartz. This relationship may be caused by the stable environment of platform basin, platform depression and lagoon, which is favorable for the formation of marine organic-rich shale, and is not conducive to the transport and deposition of terrigenous clastic clay with water. In addition, there is a certain correlation between mineral composition and kerogen type, which may be effect by the sedimentary environment, provenance and other factors (Fu et al. 2011).

However, in middle-Upper Yangtze, there is no obvious correlation between the thermal maturity and the content of clay mineral and quartz in the Paleozoic marine shale. There is an obviously linear relationship between the burial depth and the content of illite and illite/smectite formation in the clay mineral. The content of illite is obviously increased with the increase of the depth, while the illite/smectite formation is decreasing with the increasing of the depth (Fu et al. 2011). Hence, it can be concluded that the composition of the mineral is obviously correlate to the TOC. The thermal evolution of the organic matter is complemented with the transformation of clay minerals. I can be deduced that the sedimentation had influenced the enrichment of organic matter and the mineral components of shale (Li et al. 2009d). The diagenesis is mainly present by the transformation of clay minerals (Lei et al. 1995).

The organic-rich layer located at the bottom of Ordovician Wufeng Formation and Silurian Longmaxi Formation is the most favorable formation for the enrichment of shale gas

(Zhang et al. 2013a). The "deep water shelf-benthic algal mat model" is the typical model of the marine source rocks formation in Southern China (Liang et al. 2009). In marine environment, the source rock is favorable to deposited in the undercompensated environments, such as shallow-deep water basin, deep water shelf basin, deep water shelf facies (Chen et al. 2006a; Qin et al. 2009).

4. Reservoir characteristics

cMicropores and nano-pores are commonly observed in the marine organic-rich shale in China, in the forms of intergranular pores, intragranular pores and organic pores. Especially, the nano-pore throats formed after the hydrocarbon generation of organic matter, which are the main space for shale gas enrichment (Nie et al. 2009a). The nano-pore was firstly observed by Zou et al. (2011c), and was divided into organic nano-pores, nano-pores within particles and micro-fractures and so on. He has opened the prelude to the visual study of shale gas reservoir space in China.

In the study area, the porosity, permeability and pore types of the Longmaxi shale are similar to those in north America. However, due to the differences in sample collection and analysis methods, the reservoir physical tested results of the Longmaxi shale are significantly different among different scholars, although the pore types are similar. Zeng et al. (2011) pointed out that Longmaxi shale in Sichuan Basin is a compact lithology in which the porosity is often less than 2%. The micropores of shale reservoir are mainly illite flake micropores, microfractures, matrix micropores, intragranular dissolution micropores, berrylike pyrite intergranular micropores and so on. According to the helium pycnometry and pressure pulse decay experiments, the average porosity and permeability of Wufeng-Longmaxi shale are 2.11–12.46% and 0.0063–104.41 × $10^{-3}$ $\mu m^2$ in Sichuan Basin and its surrounding areas, respectively. The reservoir physics of the Wufeng-Longmaxi shales is good, except the south Sichuan Basin. The scanning electron microscopy (SEM) analysis showed that the interlayer microcracks and secondary micropores are in the organic-rich layer too. The width of the fractures is in the range of 0.5–60 μm. The diameter of secondary pore is ranging 1 $\mu m$ to 40 $\mu m$. The average face rate is 8.77% (Wang et al. 2012b). According to the test results of 33 core samples from Longmaxi Formation conducted by Weatherford, the porosity of Longmaxi shale is 1.15% to 5.80% (avg. 3.00%), and about 80% samples are bigger than 2.00%. Especially, basing on the 8 core samples of Longmaxi shale from the shale gas well with shale gas breakthrough in Weiyuan area, the porosity is 1.7–5.8% (avg. 4.2%), permeability is 0.00025–1.73700 × $10^{-15}$ $m^2$ (avg. 0.421 × $10^{-15}$ $m^2$) (Huang et al. 2012). Basing on the high-power SEM analysis of 69 samples from south Sichuan, Wang et al. (2012b) pointed out that the pore types in shale were diverse. A large number of pores and natural fractures are formed in the organic-rich shale. The pores can be divided into four types of matrix pores, such as residual primary pores, organic pores, interlamellar micropores of clay minerals, unstable mineral dissolution pores. The organic pores and the interlayer micropores between the clay minerals are the main contributors to shale reservoir space. The facture densest section is located at the lower part of Longmaxi Formation. Organic pores and interlayer micropores of clay minerals are the major component of matrix pores in shale, which is the significant difference between shale and sandstone reservoirs, and both of them are formed by the diagenesis. Basing on the reservoir physical tests of 159 core samples from the organic-rich shale section with 38 m thickness in well JY1, Guo et al. (2013) concluded that the porosity is 2.78–7.08% (avg. 4.80%), and the permeability is 0.0016–216.601 × $10^{-3}$ $\mu m^2$(avg. 0.16 × $10^{-3}$ $\mu m^2$). The reservoir space types are diverse too, including organic pores, intergranular pores, intergranular pores, dissolution pores, organic shrinkage pores, structural fractures and cleavage fractures. The permeability of the shale without fractures is commonly less than 0.01 × $10^{-3}$ $\mu m^2$. Based on the alcohol method and gas method for porosity and permeability respectively in the core sample of Longmaxi Formation from well CX-1, Chen et al. (2013a, b) pointed out the porosity is 1.92–10.64% (avg. 5.68%), and the permeability (including fracture permeability) is 2.36–32.37 × $10^{-3}$ $\mu m^2$. Basing on the characteristics of the SEM analysis of the sample from Qilong outcrops in Xishui County, Ran et al. (2014) divided the pores in shale into three types, such as micropores ($\leq$10 nm), mesoporous (10–1000 nm) and macropores ($\geq$1000 nm). Up to 10 parameters was concluded by Tu et al. (2014) to the reservoir evaluation of shale gas, including organic carbon content, organic matter maturity, effective thickness, reserve abundance, porosity, gas content, adsorbed gas content, reservoir pressure, burial depth, clay mineral content and so on. Liu et al. (2021) pointed out that the morphology of nano-pores in Wufeng-Longmaxi shale is controlled by pore location (pore type), kerogen type, burial depth, thermal maturity and pore size.

As mentioned above, the reservoir space of Wufeng-Longmaxi shale in Sichuan Basin is controlled by the mineral composition, lithofacies type, organic carbon content, maturity of organic matter and diagenesis. There are diverse types of reservoir space in Longmaxi shale, which is mainly component by organic pores, interlayer micropores of clay minerals and intergranular pores, secondary the dissolution pores and intergranular pores. Microfractures are well formed in shale, which is conducive to the reservoir physical properties and hydraulic fracturing treatments. It is reported that the organic matter in Wufeng-Longmaxi shale is composed by bitumen and kerogen. Xie et al. (2021) pointed out that there are a lot of pores in the pyrobitumen, mainly in the form of bubbles and spongy pores. However, little or no pores are observed in algal fragments, and no irregular pores are observed in bacterial aggregates. Zhu et al. (2016) pointed out that the paleontological fossils can form organic pore network system which is contribute to the pore space in shale. In Longmaxi Formation, graptolites are preserved in multi-layer carbonized films, with a few of interlayer pores and pore space in graptolites. The porosity of the graptolites shale is bigger than 2%, while the permeability is commonly smaller than $0.5 \times 10^{-3}$ $\mu m^2$. The microfractures in shale are conducive to the increasing of permeability which plays a significant role in hydrocarbon migration and shale gas exploitation. There is an obvious correlation between the reservoir characteristics and mineral composition in organic-rich shale. For example, Chen et al. (2011a, b, c, d) found that the porosity of Longmaxi Formation in Southern Sichuan Basin increases with burial depth. There is a positive correlation between porosity and the content of brittle minerals such as quartz, while a negative correlation between porosity and the content of clay. Quartz is characterized with stability mechanical, and it can act as a good supporting role in the pores. The correlation coefficient is big between the porosity and the content of quartz (Hu et al. 2021).

5. Study on diagenesis

Although the shale gas exploration in China is started much later than USA, it is based on the successful practices experience of shale gas in North America. A rapid progress has gotten in shale gas production in China. However, as the Shale gas exploration in North America, little work has carried out on the reservoir diagenesis. Previous studies on the diagenesis of shale gas reservoirs are focus on the organic geochemistry such as the TOC, thermal maturity of the source rock (Liu et al. 2011; Wang et al. 2012b; Huang et al. 2012; Zuo et al. 2012; Nie et al. 2012a, b; Li et al. 2012c; Wang et al. 2012b). The diagenesis has been concerned too (Chen et al. 2011a, b, c, d; Liang et al. 2012; Wang et al. 2012b; Li et al. 2012c). Basing on the characteristics and transformation of clay minerals in organic-rich shale in Southeastern Chongqing and their influence on reservoir physical properties analysis, Li et al. (2012c) deduced that a lot of micro-fractures were formed in the illitization process of smectite produced micro-fractures, which is a part of the storage and permeability space in shale reservoirs. Wang et al. (2012b) pointed out that diagenetic stage is closely related to the brittleness of shale reservoir. During the late maturity or metamorphosis stage, the minerals in shale are gradually transformed into brittle and stable minerals. A large-scale reservoir conditions is an indispensable condition to the enrichment and high yield of shale gas. With the effect of compression, little primary pore was resided in the shale. The reservoir space in shale is mainly composed by the secondary pores and fractures which are formed by the hydrocarbon generation, transformation of clay minerals and the dissolution of unstable minerals (Liu et al. 2011; Wang et al. 2012b). In consider of the influence of mineral formation (e.g., quartz, dolomite and pyrite) on the shale gas reservoir condition during the diagenetic stage, Wang et al. (2021) pointed out that hyomorphic pyrite, bioquartz and microbial dolomite were mainly formed in the early stage of syngenic-early diagenetic stage, which is with the destructive and constructive dual effects on the preservation of original pores in shale. It is supported that the framework dominated the formation of high-quality shale reservoir. The rigid support framework composed of such minerals and terrigenous debris is beneficial to the preservation of original pores and later fracturing. Zhou et al. (2021) concluded that the carbonate minerals Wufeng -Longmaxi shale are derivatives of methanogen metabolism at the early burial stage of sediments. The carbonate mineral is benefit to the brittleness of shale which improves drillability and fracturing effect of shale reservoir. As for the division of diagenetic stages, Chen et al. (2011a) pointed out that the Longmaxi shale is characterized with high illite content stable over the Sichuan Basin, which indicated that the Longmaxi shale has enter into the late diagenetic stage. The diagenetic degree of Longmaxi shale in Southern Sichuan Basin is appropriate to the enrichment of shale in consider of the thermal evolution conditions. As the source rock in Sichuan Basin, the shale gas reservoir was experienced by organic and inorganic processes diagenesis during burial. The formation process of shale gas reservoir is relatively complicated. Basing on the analysis of pores influenced by the diagenesis of organic-rich shale in lower Qiongzhusi Formation in well NJ-1, Fu et al. (2015) pointed out that some pores were cemented and filled by the dissolved silicon recrystallization during diagenesis. The pores are gradually becoming closed or semi-closed pores with the increase of quartz content, and the porosity is decreased. Hence, the diagenesis study in shale gas discipline (especially shale gas in China) has still in the primary stage now. Up to now, few comprehensive and systematic study has been carried out on the diagenesis and diagenetic evolution of shale gas reservoirs.

6. The characteristics and evaluation of gas reservoirs

According to the tested data from the core samples from well CX-1 in south Sichuan Basin, the commercial value of shale gas is dominated by the content of free gas and adsorbed gas. The content of free gas is closely related to its structure. However, the adsorption gas is affected by environmental factors such as temperature, pressure and so on. In the same condition, the adsorption volume is positively correlated with the organic matter content (Wang et al. 2009a, b, c). The organic carbon content is positively correlated with gas content in well CX-1. It can be concluded that the richer of organic matter the bigger total gas content in the shale. Longmaxi Formation is favorable for the enrichment of shale gas for the characteristics of it such as, big TOC, high thermal maturity, with micro-fractures, appropriate burial depth. Therefore, the shale gas reservoir was mainly evaluated according to the TOC at the initial stage of shale gas in China.

Kerogen and clay minerals in shale is an important carrier for the adsorption hydrocarbon. The characteristics of pores in shale and its gas adsorption capacity is not only controlled by the type of clay minerals, but also the thermal maturity and the petrogenetic of shale. The specific area of shale is influenced by the content of micro pores in shale to, which is dominated the adsorb ability of the shale (Ji et al. 2012). Hence, the shale gas reservoir evaluation should be based on petrological study. In addition to petrology and physical properties studies as the evaluation of conventional reservoirs, the evaluation of shale reservoirs should take the total gas content and the technical feasibility into consider (Zhu et al. 2009). Longmaxi shale has been in the hypermaturity stage (Zou et al. 2010a). The gas in the shale is mainly in the form of free and adsorbed state, little is in the dissolved state (Wang et al. 2011a). Basing on the simulation study of lower Cambrian shale in Western Hubei, Fang et al. (2021) pointed out that the shale gas is mainly component by the free gas, secondary adsorb gas. Hence, the study of pores and the composition of free and adsorbed gas are with great significance to revealing the gas-bearing characteristics of shale. Under a certain temperature–pressure condition, the adsorption gas content is positively correlated to the organic carbon content. Meanwhile, the content of adsorb gas is also significantly correlated with the type of organic matter, thermal maturity, mineral composition (especially clay minerals), humidity (water content) and pore structure (Hao et al. 2013). Adsorption capacity is one of the important indicators for shale gas reservoir evaluation. The evaluation parameters include lithological association, mineral composition, tectonic structure, TOC, vitrinite reflectance ($R_o$), kerogen type and diagenesis (Yu et al. 2012). Basing on the analysis of the adsorption characteristics of shale and the difficulties would be faced in shale gas exploration in China, Hao et al. (2013) pointed out that the adsorption capacity of the shale is influenced by the characteristics of organic matter (enrichment degree, type and maturity), mineral composition, pore size and structure, water content and regional temperature–pressure condition. Zhang et al. (2012b) found that the higher thermal maturity the more adsorbed gas in shale. In organic-rich shale, the adsorption capacity of minerals to gas is weaker than that of organic matter. In the laboratory, the gas adsorption capacity is directly proportional to pressure and inversely proportional to temperature (Zhang et al. 2012b). In practices, the adsorption capacity of shale is affected by pressure and increases with the increase of burial depth but decreases with the increasing of temperature when it reaches a certain extent (Hao et al. 2013). Basing on the analysis of state and content of gas in shale influenced by the composition of shale, tectonic and geological conditions, Jiang et al. (2016a, b) and Zou et al. (2015, 2016) pointed out that the gas in shale is mainly in the state of adsorption and free state, which is closely related to the temperature–pressure (depth) condition. The composition ratio of adsorbed and free gas is a direct impact on the occurrence characteristics of shale gas, which should be paid attention.

The experimental and analogical studies on the enrichment of shale gas have been carried out by the Chinese scholars, basing on the experience of shale gas production of USA and the lithologic characteristics, hydrocarbon generation capacity, hydrocarbon accumulation capacity of shale in China (Li et al. 2009d; Jiang et al. 2010; Liang et al. 2012). Zhong et al. (2019) pointed out that the shale gas reservoirs in the Wufeng-Longmaxi Formation are with six features, such as organic geochemical characteristics, gas content, lithology and mineral composition, brittleness (fractured ability), physical properties and heterogeneity of the gas reservoirs. Liang et al. (2016) concluded the key factors influenced the enrichment of shale gas in Sichuan Basin are included: (1) a huge thick organic-rich shale which provides a hydrocarbon basis for shale gas; (2) an enclosed environment which is conducive to the preservation of shale gas; (3) a huge number of organic pores which provides space for the reservoir of shale gas; (4) the intensive fractures in brittle sections which is contribute to the reservoir space of shale; (5) the dense high-angle fractures are beneficial to the formation of complex fracture networks in later fracturing treatment. (6) compressional faults are favorable for shale gas preservation for its good plugging ability. One typical feature has been observed in the Wufeng-Longmaxi Formation, which is the total gas content are commonly different in different areas (Fig. 1.2). Basing on the statistical analysis more than 600 shale samples from Wufeng-Longmaxi Formations, Qiu et al. (2019) pointed out that the gas content is obviously varied in vertical. The smaller one is almost on gas content, while the biggest one is 9.0m$^3$/t. There are great differences in gas content in favorable (enrichment) and sweet spots, according to the comparative analysis of different regions such as Weiyuan, Changning, Fuling and Wuxi are the main areas. An important feature of Wufeng-Longmaxi shale gas is the pressure coefficient of it (Fig. 1.2). According to the classification criteria of natural gas reservoirs, shale gas reservoirs can be divided into low-pressure gas reservoirs (pressure coefficient < 0.9), atmospheric pressure gas reservoirs (0.9 $\leq$ pressure coefficient < 1.3), high-pressure gas reservoirs (1.3 $\leq$ pressure coefficient < 1.8) and ultra-high-pressure gas reservoirs (pressure coefficient $\geq$ 1.8). The overpressure is commonly observed in Sichuan Basin, such as the Jiaoshiba and Changning-Weiyuan shale gas field where the shale gas has been commercially exploited (Fig. 1.2). Guo et al. (2014) pointed out that the shale gas enrichment and the total resources of shale gas are dominated by the porosity and formation pressure. Hu et al. (2014) concluded that the formation pressure coefficient is a good indicator for preservation conditions the of shale gas. The over pressure is commonly indicted a good preservation condition of shale gas. The formation mechanism of overpressure has been studied Zhang et al. (2016). It is concluded that the bigger TOC is the basic condition for overpressure in shale strata. The higher thermal evolution the more gas is cracked, which is more benefit to formation the overpressure. The preservation of overpressure is closely correlated to the uplifting process too. In conclusion, the shale gas in Wufeng-Longmaxi Formations is characterized with high thermal evolution and ultra-overpressure. The gas is mainly in the free gas state in the overpressure area. The enrichment of shale gas is influenced by the adsorption of shale, the trap of capillary pressure and slowly diffusion, which is named “micro residual enrichment model” by (Tenger et al. 2017).

The atmospheric pressure shale gas reservoirs are commonly observed in Sichuan Basin (Fig. 1.2). According to the structural conditions, shale quality and production characteristics in Sichuan Basin and its surrounding area, Nie et al. (2019) divided the pressure shale gas reservoirs in Wufeng-Longmaxi Formations into four types, such as organic-rich eroded away or denudation type, early diffusion type, fracture or fault damaged type and residual syncline type. Meanwhile, Nie et al. (2019) deduced that although atmospheric pressure shale gas reservoirs are characterized with poor-middle enriched and medium–low quality shale, large total resources and huge reserves may be preserved in some area. Guo et al. (2020) proposed that favorable atmospheric shale gas reservoirs can be predicted with the following parameters, such as TOC > 3%, porosity > 3% and total gas content > 3$m^3$/t in the complex structural areas outside the basin.

In the primary stage, the favorable area for shale gas had been predicted by the analogy analysis between China and the five shale gas production areas in USA. Most of the scholars predicted the favorable area for shale gas by taking into account of the shale thickness, buried depth, TOC and $R_o$. Partly scholars took the isothermal adsorption capacity in to account too, which optimized the parameters for predicting the favorable target area for shale gas. However, little total gas content data can be obtained in the pre-drilling stage. Hence, in the primary stage, the prediction of favorable areas for shale gas in China actually was a prediction on the organic-rich shale, which has not entered into the optimization stage of shale gas. According to the primary stage of shale gas exploration in China, the shale gas resources are widely distributed in China. Marine strata in south China are with superior geological conditions for shale gas accumulation and abundant shale gas resources, which is expected to become an important strategic replacement area for oil and gas resources in China. Especially, the Sichuan Basin deserves the first attention (Zhu et al. 2010).

There are many factors affecting the scale exploitation of shale gas. The key factor is the reliability of geological evaluation criteria for core area. The determination of the core area is related to whether the target of maximum enrichment of shale gas can be identified in the early stage of shale gas exploration. If the core area is predicted reliability, the shale gas flow will be obtained which is the basement to achieve large-scale economic exploitation in later period (Wang et al. 2012b). The favorable areas and its geological characteristics are commonly different among different studies, for the geological evaluation criteria for shale gas is inconformity among different scholars. For example, Wang et al. (2012c) proposed that the core area for shale gas in Wufeng-Longmaxi Formations in Sichuan Basin should be with big thickness (mostly 40–100 m black shale thickness), big TOC (> 1.5% in most areas), high thermal maturity (*R*o. avg. 1.49–3.135) and big total gas content (avg. > 2 $m^3$/t). Zuo et al. (2012) proposed that there are seven key geological factors for predicting the favorable area for shale gas in Southeast Sichuan Basin, such as abundance of organic matter, thermal maturity, organic matter type, brittle mineral content, shale thickness, burial depth and structural configuration. The evaluation criteria for favorable exploration areas are as follow, (1) thickness of organic-rich shale is > 100 m; (2) the top burial depth of Longmaxi shale is shallower than 2400 m; (3) TOC > 2%; (4) *R*o > 1.3%; (5) regional tectonic strength is weak. Huang et al. (2012) pointed out that the favorable areas for shale gas in Longmaxi Formation in Southern Sichuan Basin is characterized with TOC (0.50–8.32%, avg. 2.53%), effective thickness (20–260 m) at the lower section of Longmaxi Formation, sapropelic-type kerogen, Ro (>1.8%), in high to hypermaturity stage, with nanoscale pores, porosity (1.15–5.80%, avg. 3.00%), enrich brittle minerals, big total gas content (0.3–5.1 $m^3$/t, avg. 1.9 $m^3$/t), total hydrocarbon is abundant. The areas may be great shale gas resource potential with buried depth (<3600 m).

The preliminary geological evaluation standard for China's shale gas core area is established by Wang et al. (2012b),

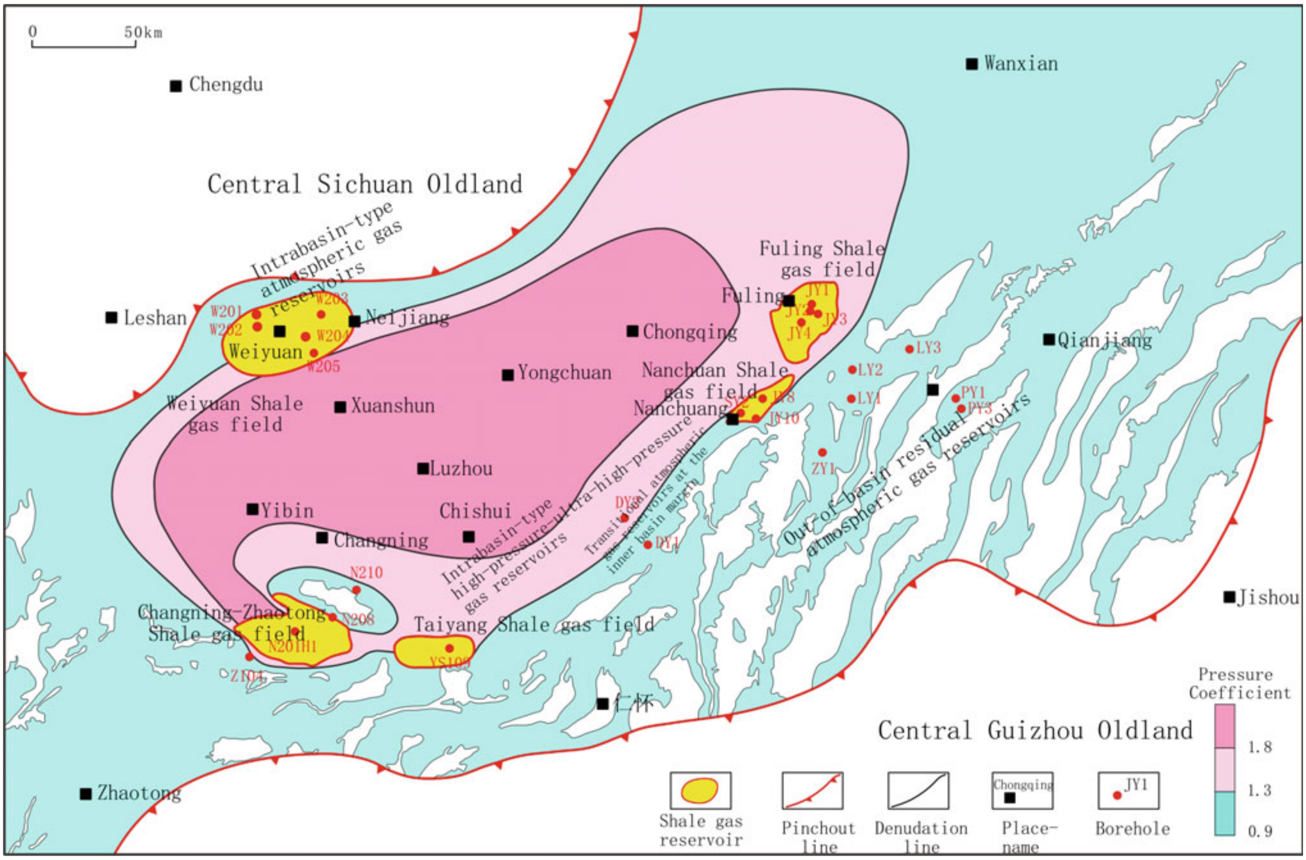


**Fig. 1.2** Distribution characteristics of pressure coefficient in Wufeng-Longmaxi Shale gas reservoirs in Sichuan Basin and its surrounding area

basing on the experience of shale gas production of North American and the research progress of China shale gas. The core areas for shale gas have been selected out in Southern Sichuan Basin. Meanwhile it concluded that the Southern Sichuan Basin is the most realistic shale gas development zone in China. Li et al. (2013b) established a set of evaluation index system suitable for high-evolution marine shale gas in Southern Sichuan Basin based on the research results of various indicators. Good results have been gotten by applied this system to the core area selection and potential evaluation of Longmaxi shale gas in Southern Sichuan Basin.

Furthermore, the terrestrial shale gas study has been started early. For example, the enrichment condition and the exploration potential has been studied by Ye and Zeng (2008). They found that the favorable shale in Xujiahe Formation is the dark shale mainly deposited in littoral lake swamp and inland lake swamp facies. Basing on the analysis of shale gas geological conditions, Zhang et al. (2008) pointed out there might be a huge amount of shale gas resources in paleogene Shahejie Formation in Jiyang Depression. Zhou et al. (2011) has discussed the reservoir-forming conditions and exploration direction of Mesozoic lacustrine sedimentary shale gas in Fuxian block, Ordos Basin. Wang et al. (2011a, b) has evaluated the shale gas condition in the Ordovician Marine shale, carboniferous-Permian Marine and continental transitional shale and upper Triassic lacustrine shale in Ordos Basin and pointed out that the latter two layers are with the potential to form shale gas reservoirs. Yang et al. (2013) has studied the characteristics of micro pores in shale and its geological significance to the enrichment of shale gas in continental shale in Ordos Basin. He pointed out the enrichment and migration of shale gas is mainly contributed by the intergranular pore in clay minerals content aggregation and intragranular pore between the layers. The two types of intergranular pores are main control factors of reservoir permeability anisotropy, secondary the intergranular pore and dissolution pore. Organic pores may contribute less due to it is very rare. At the same time, the influence of microcracks cannot be ignored, which is the main microchannel connecting the macropores and mesopores. Lin et al. (2013a, b) analyzed the geological conditions and organic geochemical parameters of terrestrial organic-rich shale, by concluding the distribution of terrestrial organic-rich shale in China. It is concluded that the continental organic-rich shale in China is mainly distributed in the Middle Cenozoic in north and Northeast China, Northwest China and some parts of south China. On the whole, the terrestrial shale gas enrichment in China is characterized with large cumulative thickness, diverse types of organic matter, with a lot of reservoir space, good preservation conditions, high abundance of resources and convenient surface conditions. Moreover, the terrestrial organic-rich shale in China mostly overlaps on the conventional oil and gas fields which with the data and equipment advantages. Therefore, it is likely with better economic recovery. At the same time, the research on shale gas in China is mainly focused on basic theory. The geophysical method using to the shale gas exploration has still in the primary stage. Basing on the analysis of geological and geophysical response characteristics of organic-rich layer in Southern Sichuan Basin, Li et al. (2011a) has established a set of geophysical technical process for shale gas exploration, through the research for seismic data acquisition, processing and interpretation. And, some new progress has been obtained in the seismic exploration of shale gas. In addition, Chen et al. (2011a) systematically studied the formation conditions of shale gas in Hetaoyuan Formation of Cenozoic lacustrine basin-Biyang Depression of Nanxiang basin for the first time, by referring to the evaluation indexes of marine shale gas in the USA.

## 1.2 Current Status of Lithofacies Paleogeography

Lithofacies paleogeography is an important branch of modern sedimentary geology, which originated from sedimentology. Its development has a close relationship with the development of sedimentology. Lithofacies paleogeography can become a branch of discipline, which is related to the development of sedimentary petrology into sedimentology, and this learning process is inseparable. In a sense, sedimentology is the main basis for the study of lithofacies paleogeography. Now, however, its research scope has already gone beyond sedimentary petrology. Based on a high integration and intersection of various geological disciplines, and supported by the theory of tectonic activity and dynamic transformation, it focuses on investigating and studying the reorganization of oceans and land, distribution of land and sea, nature of basins, ecological environment and allocation of mineral resources from a global perspective (Mou et al. 2016a).

### 1.2.1 Development History of Foreign Lithofacies Paleogeography

Due to lack of theoretical guidance, the original sedimentology basically describing the appearance of sedimentary rocks, focusing on studying and describing their external features and trying to explain their causes. Until 1830, Lyell proposed the idea of "Uniformity Theory", including the "Walther law of facies" proposed by Walter at the same time. For a long time in the future, research in the geological community will be based on these guiding ideologies (Hua and Zhang 2009).

Until 1939, Twenhofel published the book of the Principles of Sedimentation and Trask published the book of the Modern Marine Sedimentation. They explored the characteristics of modern sedimentary environment in methodology and provided necessary tools for explaining ancient geological history (Hua and Zhang 2009). This is also one of the most important and commonly used principles and methods in the development of sedimentology, that is, to speculate the formation environment of ancient sedimentary rocks according to the modern sediment forming environment, conditions and climates of modern sediments can be summarized as "present being a key to past". In addition, the principle and method of particle size classification of debris particles proposed by Udden, Wentworth, etc., conforming to the laws of Fluid Mechanics and the Normal Distribution of particles; Boggs researched on micro-petrology of sedimentary rock and Milner applied mineral research on provenance and stratigraphic correlation division, etc. These typical examples represent the origin stage of sedimentary-based lithofacies paleogeography. It could be said that the lithofacies paleogeography and related mapping works (methods) at the origin stage have little relation with mineral resources and energy resources.

The World War II and the reconstruction for various countries after the war intensified demand for energy and minerals, which indirectly contributed to the rapid development of sedimentology and lithofacies paleogeography. Among them, the most important is a large number of new technologies and methods to continuously used in sedimentology, which makes the comprehensive development of various testing technologies in this period become mainstream, such as the application of X-ray diffraction and mathematical statistics in particle size analysis (Hua and Zhang 2009). Typical examples are as follows: In 1935, based on the study of sedimentary mineral components, Peitizhuang compiled the contour map of sedimentary mineral components for the first time according to the content and characteristics of different mineral components. In 1949, Sedimentary Rocks was published, which studied the classification of sedimentary rocks and discussed the strata and tectonic environments. It was the first research work on systematic classification in the history of sedimentology. The main task of sedimentology is to infer the paleoenvironmental characteristics of rock strata. In 1945, Krubin not only obtained the paleosedimentary environment of the research object through a great deal of research, but also made a quantitative study on the material expression (rocks, etc.) of the sedimentary environment and concluded that "boundary conditions, particles and hydrodynamic conditions (energy) are the three main factors in the sedimentary system", which enriched the relevant knowledge of sedimentology. In the research history of sedimentary basin analysis, Pettijohn and Crews (Cloos) also systematically used paleocurrent direction and rock correlation to conduct a preliminary analysis, which is the first time in the field of sedimentology. The innovation and application of these theories and methods not only directly promoted the development of sedimentology itself, but also accelerated the development of lithofacies paleogeography and gradually deepened the relationship between this discipline and mineral and energy resources. This is the stage of development of sedimentology and lithofacies paleogeography.

Sedimentology and lithofacies paleogeography entered the modern research stage after 1950, which was marked by the most famous, representative and innovative theory, "Turbulence Theory", which was a milestone in the development history of sedimentology and lithofacies paleogeography. Subsequently, under the guidance of Kuenen, Bouma further proposed the "Bauma sequence" model. The next 20 years or so also witnessed the rapid development of sedimentology and lithofacies paleogeography, and a large number of high-level summative and innovative monographs were published: Sedimentary Petrology and Sedimentology by Douglas, Analysis of Paleocurrent and Basin by Pettijohn and Porter, etc. Among them, there are several works and theories of great significance: the first is the classification of limestone published by Fok (1959, 1962), which is a very important breakthrough in the study of sedimentary facies of carbonate rocks; Secondly, mechanical concepts such as fluid flow pattern, Reynolds and Froude numbers were introduced into sedimentology, which greatly promoted the hydraulic interpretation of sedimentary structures and the study of formation mechanism. The flume experiment of Simons and Richardson (1961), in which the concept of water flow dynamics was formulated to explain the sequence of sedimentary structures, has since established the basis for sedimentology and lithofacies paleogeography. Then, there is the theory of plate tectonics developed from Wegener's continental drift theory and the seafloor spreading theory of American seismic geologists Dietz and Holden (1970) and Heirtzler (1969). Mckenzie and Parker, Princeton University's Morgan and Lamont Observatory (France) Pichon and others jointly put forward, it is a specific extension of the theory of seafloor spreading and finally published by Morgan and Series. In the same year, French geologist Pichon divides the earth's rock strata into six plates, namely the Pacific plate, the Eurasian plate, the American plate, the Indian Ocean plate, the African plate and the Antarctic plate. This theory provides a basis (theoretical basis) for understanding the large-scale distribution of sedimentary facies and biota, as well as the migration of the crust, thus prompting sedimentologists and paleogeographers to consider the influence of structure and plate movement on sedimentation. Therefore, a new discipline, basin analysis, has also been developed.

In short, from 1950s to mid-1970s, because of the background of global geological research, many geologists found that although sedimentary rocks contained a large variety of extremely important mineral resources, some of them only occurs in sedimentary rocks. In order to study the occurrence and distribution of these minerals and petroleum and further expand their exploitation scope, many researchers began to pay attention to the origin and nature of sedimentology and lithofacies paleogeography, as well as their deep relationships with minerals and petroleum and relationships including causal relationships, spatial relationships and so on. The results prove that the paleoenvironment or paleogeography not only controls the formation of sedimentary layered deposits, oil, gas, etc., but also controls the formation and enrichment of many-layered deposits. Therefore, it is very important to study the natural geographical environment when sedimentary rocks were formed. Essentially, the continuous innovation of theories and methods related to sedimentology and lithofacies paleogeography has also fundamentally guides the deepening of research and exploration in the field of mineral and the petroleum industry and made great achievements. This knowledge should be very important in the development of sedimentology and lithofacies paleogeography in this period.

From the late 1970s to the 1980s, the development of sedimentology and lithofacies paleogeography should have matured. Many sedimentologists not only supplemented and improved the various theories and methods of their predecessors, but also put forward many more constructive theories and methods. The development of stratigraphic stratigraphy based on seismic stratigraphy not only enriched the theory of sedimentology, but more importantly, provided the basis and methods for the preparation of more accurate paleogeographic maps, with representative works such as seismic stratigraphy in oil and gas exploration (Vail 1977) and principles of stratigraphy (Vail and Posamentier 1988). The global ocean anoxic event discovered (proposed) by Schlanger and Jenkyns (1976) according to the plate tectonic theory provides an excellent foundation and methodology for global research. It is worth noting that the theoretical basis and methods are put forward for mineral resources and oil and gas resources. The former being based on the oil and gas industry foundation, then researched and put forward and finally served for the research, exploration and development of oil and gas; the latter having mineral and hydrocarbon resources due to the anoxic seabed, where the sediments are black and rich in organic carbon, generally not disturbed by benthos and often form marine striped sediment containing pyrite and heavy metals. Generally speaking, the development of sedimentology and lithofacies paleogeography in this period is inextricably linked with mineral resources and energy resources (such as hydrocarbons) and guides the research, exploration and development of mineral resources and the hydrocarbon industry.

Since 1990s, sedimentology and lithofacies paleogeography have entered a period of modern comprehensive development. Information from the International Association of Sedimentologists (IAS) (the 12th to 19th, 1986–2014) from 1986 to 2014 shows that contemporary sedimentologists have not only placed greater emphasis on basic sedimentological and lithofacies paleogeographic research (summarised as the process of refining the theoretical system of sedimentology), but also strengthened new sedimentological research methods with a view to increasing the understanding of the sedimentary environment of “sedimentary rocks” from a more detailed macro- and microscopic and integrated perspective, thus better serving the recovery of the paleoenvironment and paleogeography, and thus enabling accurate predictions of the genesis and spatial distribution of mineral and energy resources. On this basis, we will seize contemporary hot issues and conduct targeted research. The specific mainstream development directions are: high-precision sequence stratigraphy research (covering the compilation method of high-precision lithofacies paleogeographic map, instantaneous lithofacies paleogeographic map, global sea level change (curve) research, etc.) sedimentary basin analysis (especially sedimentary basin analysis in complex orogenic belts), dolomite genesis research, deep-water sedimentation and sedimentation research, sedimentary structure evolution and sedimentary response research, climate, environmental change and resource sedimentology research, etc. Another particularly important research status and the trend is the comprehensive research of interdisciplinary and cross-penetration. Nowadays, the concept of time coordinates has not only been introduced into the understanding of sedimentological laws, but also closely integrated with tectonic theory, earthquake-sequence stratigraphy, geophysics, geochemistry and computers, etc., using “new methods and new technologies”. Begin to explore the regularity of sediment movement in four-dimensional space (Jiang et al. 2014), to better serve basic geological research, mineral and energy industry development, etc. This will be the development trend and direction of the contemporary and future sedimentology research model with “sedimentology, supported by multidisciplinary integration and cutting-edge technology” (Liu et al. 2006; Zhang and Xin 2006; Jiang et al. 2007; Hua and Zhang 2009; Zheng et al. 2013a, b; Jiang et al. 2014).

It is not difficult to see that the development history of sedimentology and lithofacies paleogeography abroad (Table 1.1) is also the development history of mineral and energy industries to some extent. Among them, oil–gas sedimentology, sequence stratigraphy derived from sedimentology, etc., combined with geophysics, geochemistry and other comprehensive disciplines, have achieved good results in the research of mineral resources and energy resources. They not only fully display sedimentology and lithofacies paleogeography at macro- and micro-levels, but also make the research more comprehensive and accurate and has been applied to the exploration and development of mineral resources and energy resources. In a word, the theories and technologies of sedimentology and lithofacies paleogeography accompany and guided the rapid development of the mineral and energy industries.

### 1.2.2 Research Status of Lithofacies Paleogeography in China

The study of lithofacies paleogeography in China started early. Although the related theories and methods are relatively lacking in innovation, most of them are the basis for the theories and methods of sedimentology and lithofacies paleogeography abroad. In the past, theoretical supplements or fruitful innovations were made according to Chinese geological conditions, but considerable progress and remarkable achievements were made.

In the aspect of restoring paleoenvironment or paleogeography, the lithofacies paleogeography research in different periods in China have produced different mapping guiding ideologies, principles and methods and formed corresponding representative monographs or achievements (Mou et al. 2016b). In chronological order, in the 1950s, Mr. Liu (1955) compiled the earliest large-scale paleogeographic atlas of lithofacies in China, “Paleogeographic Map of China” based on stratigraphy. In 1965, Lu Yanhao, a paleontologist, compiled Cambrian Paleogeography from the perspective of paleobiogeography (Lu et al. 1965). In 1984, Guan Shicong compiled “Sedimentary Facies and Oil and Gas in Chinese Sea-Continent Change Sea Areas”, taking sedimentology as the theoretical basis and combining the knowledge of geotectonics, stratigraphy, petroleum and natural gas geology and other disciplines), which is the first attempt in China to apply sedimentology and lithofacies paleogeography to oil and gas energy resources. In 1985, Professor Wang Hongzhen and his team kept pace with the times, adopted the idea of “tectonic activity theory” and “geological historical evolution stage theory” and compiled the “Chinese Paleogeographic Atlas” (Wang et al. 1985). It not only has some innovations and breakthrough in mapping idea, but also is ingenious in map expression: although the overall shape of the map is still plotted with the present latitude and longitude, the main continental blocks in China and the tectonic boundary with the orogenic belt are used in the crust. Docking subduction zones and crustal

**Table 1.1** Time and significance of important theories (events) in the development of sedimentology (after Jiang et al. 2014)

| Stage | Time | Theory (event) | Representative | Significance |
|---|---|---|---|---|
| Budding in its initial formative stages | 1830–1839 | Geological theory, the past and the present | Lyell CC, Trask | The realist principle of discussing the present and the past |
| | 1884 | Deep-sea sediments | Murray J | Classification and description of deep-sea sediments |
| | 1894 | Introduction to geology for historical sciences | Walther J | Propose the "phase sequence" law |
| | 1913 | Sedimentary petrology | Hatch FH | Sedimentary petrology was separated from stratigraphy and gradually became a unique part of the earth sciences<br>The sub-discipline was established; and the study of sedimentation began to be emphasized |
| | 1922 | Introduction to sedimentary petrology | Milner HB | |
| | 1926 | Sedimentation tutorial | Twenhofel WH | |
| | 1931 | Journal of Sedimentary Petrology | Founding of the American SEPM Society | Marks sedimentology as a separate discipline |
| | 1932 | Phase theory | Налцвкций Д. В | |
| | 1932 | Sedimentary petrology | Швецов | From qualitative research to semi-quantitative research, more emphasis is placed on sedimentation and deposition<br>Study on the formation mechanism of sedimentary petrology, an important sign of the maturity of sedimentary petrology |
| | 1939 | Principle of sedimentation | Twenhofel WH | |
| | 1935, 1949 | Sedimentary rocks and sedimentary minerals research | Pettijohn FJ | The first contour map of sedimentary mineral composition, an important sign of sedimentary petrology maturity |
| | 1950 | Turbidity current is the reason for the formation of graded bedding, turbidity current theory | Kuenen PH | Opened a new chapter in the study of turbidity current, a milestone in the history of sedimentology and lithofacies paleogeography research and development |
| Sedimentary petrology | 1951 | "Sedimentary Petrology", "Theoretical Basis of Sedimentary Genesis", "Analysis of Paleoflow Water and Basin", "Genesis of Sedimentary Rocks" by H.Blattetal, "Sedimentary Facies and Sedimentary Environment" | Deoglas DJ, Trahov, Petty Zhuang and Porter, Blattetal H, Reading | Sedimentology is a new stage in the development of sedimentary petrology |
| | 1952 | International sedimentological society founded (IAS) | | Publish the latest research results in the field of sedimentology, promote international cooperation and exchanges, advocate<br>Guide multi-disciplinary cross-integration and promote global sedimentology research and exchange services |
| | 1959, 1962 | Practical petrological classification of limestone, mechanical concepts such as fluid state concept, Reynolds and Froude numbers are introduced into sedimentology | Simons and Richardson | Carbonatite research has entered a new stage, and the study of sedimentology and lithofacies paleogeography has a basis for sedimentary dynamics |
| | 1961, 1968 | Development of the theory of plate tectonics from the theory of continental drift and seafloor spreading | Alfred Lothar Wegener, Dietz R, Hess H, Mckenzin DP, Parker RL, Morgan WJ, Lepichon X | This has provided the basis (theoretical basis) for understanding the widespread spread of sedimentary phases and biogenic assemblages, as well as the transport of crustal material, which has led sedimentologists and paleogeographies to consider the effects of tectonism and plate movement on sedimentation and paleogeographic change, and thus to the development of a new discipline, basin analysis |
| | 1961 | Turbidite | Bouma AH | Propose the famous "Boma sequence' |
| | 1962 | Sedimentary rock research methods | Liu Baojun | The beginning of the development of sedimentary petrology in China and the establishment of a theoretical system of sedimentology |
| | 1962 | Sedimentary petrology | Wu Chongjun | |
| | 1964 | Structural genetic classification of carbonatite | Ye Zhizheng, He Qixiang, etc | The beginning of the modern concept of carbonatite research in China |
| | 1970 | The beginning of the modern concept of carbonatite research in China | Pieson SJ | First to use logging for oilfield sedimentology studies |

(continued)

**Table 1.1** (continued)

| Stage | Time | Theory (event) | Representative | Significance |
|---|---|---|---|---|
| All-round development of sedimentology | 1977, 1978 | Seismic stratigraphy, comprehensive analysis of sea level change, "Application of seismic stratigraphy in oil and gas exploration"<br>Global oceanic hypoxia event | Vail PR, Schlanger S | Combine sedimentary facies analysis with seismic data, introduce the concept of sequence and propose the concept of isochronous stratigraphic framework<br>The global oceanic anoxic event proposed by Schlanger, based on the theory of plate tectonics, provides a good foundation and method for global research |
| | 1984 | Principles of sedimentary basin analysis | Miall AD | Synthesis of structural geology and sedimentology |
| | 1988 | "Principles of Sequence Stratigraphy" | Vail PR | The development of stratigraphic stratigraphy based on seismic stratigraphy has not only enriched the theory of sedimentology, but more importantly has provided the basis and methodology for the preparation of more accurate paleogeographic maps |
| | 1986–2010 | 12th International Congress of Sedimentology | Hosted by the International Sedimentary Society (IAS) | Emphasis on the basic research of sedimentology, while strengthening new research methods; sequence stratigraphy and sedimentary basin analysis, global sea level change, carbonate rock and dolomitization research become mainstream; high-precision sequence stratigraphy, deep water Sedimentation and sedimentation, diagenesis, sedimentary tectonic evolution, climate, environmental changes, and resource sedimentology continue to be the focus of research, representing the development direction of sedimentology |
| | | Thirteenth International Congress of Sedimentology | | |
| | | 14th International Congress of Sedimentology | | |
| | | 15th International Congress of Sedimentology | | |
| | | 16th International Congress of Sedimentology | | |
| | | 17th International Congress of Sedimentology | | |
| | | 18th International Congress of Sedimentology | | |
| | 2010–present | The main trend in the development of sedimentology is the cross-pollination and integration of various disciplines. This is reflected in the introduction of the concept of time coordinates in the understanding of sedimentological laws, but also in the close integration with geotectonic theory, seismic-stratigraphic stratigraphy, geophysics, geochemistry and computers, etc., and the use of "new methods and techniques" to begin to explore the regularity of sediment movement in four dimensions. The aim is to better serve basic geological research, mineral, and energy industry development, etc. This will be the development trend and direction of the contemporary and future sedimentology research model based on "sedimentology, supported by multidisciplinary integration and frontier technology" | | |

superimposed subduction zones represent their tectonic divisions and related properties, which are consistent with the idea of "tectonic activity theory" in the idea of compiling maps; the second is the evolutionary nature of the ocean-continent transition process between continental blocks in China. The final description of the orogenic form between them is consistent with the "geological historical evolutionary stage theory" in the idea of compiling maps. This is the first generation of lithofacies paleogeography atlas in China. It is not only the Chinese sedimentology, but also the breakthrough and innovation of the whole geoscience research, which has important guiding and enlightening significance.

After the 1990s, sedimentology and lithofacies paleogeography in China entered a period of development in which a hundred schools of thought competed, drawing on and absorbing the guiding ideas of the "activity theory" from abroad, and the "geological activity theory" in China, which was used to compile "fixed theory" lithofacies paleogeographic maps within the present-day coordinates of latitude and longitude in China, with emphasis on "petrographic or sedimentary" elements (Mou et al. 2016b). Representative figures and works include Liu Baojun and Xu Xiusong, who proposed the idea of "tectonic control of basins and basin control of phases" in the compilation of maps and compiled the Atlas of South China Earthquake - Triassic Lithofacies Paleogeography (Liu et al. 1994). In summary, this paleogeographic atlas has the following two features: (1) the idea of "structure controlling basin and basin controlling facies" was adopted for the first time in China to compile lithofacies paleogeographic map set, and the compiled paleogeographic map fully considered the crustal evolution background of each fault stratum in each geological history period and reflected its structure and basin nature in the form of corner maps. The paleogeographic map is a preliminary attempt at dynamic paleogeographic recovery (Mou et al. 2016b); (2) it focuses on dissecting the tectonic and basin-embedded properties of the sediments, emphasizing them as a comprehensive causal body of tectonic subsidence, sea-level rise and fall and material supply rates and also focuses on the effects of event deposition and continental margin evolution, etc. Another example is the quantitative lithofacies paleogeographic mapping method pioneered by Feng Zengzhao, which adopts a "single-factor analysis and multi-factor synthesis" approach to compile a series of quantitative lithofacies paleogeographic maps of various regions and selected geological periods in China (Feng and Wu 1988; Feng 1991; Feng et al. 1994, 1997a, b, 1999), such mapping methods have been widely applied in the field of oil and gas exploration and development in China (Mou et al. 2016b), a typical example of the application of Chinese lithofacies paleogeography to the oil and gas industry. Of course, in the early research stage of the oil and gas industry, there are many typical examples of lithofacies paleogeography and its mapping methods as the main guiding ideology, for example, the application of lithofacies paleogeography and its mapping methods played a key role in the discovery of the Puguang gas field in China. The collaborative team of Ma et al. (2002, 2005; Ma and Cai 2006; Ma et al. 2009), Mou et al. (2003) and others compiled a more detailed lithofacies paleogeography map of the Changxing Formation in the Northeast Sichuan area after detailed studies of the sedimentary phases and sedimentary micro levels, which was a key guide for oil and gas field companies in good deployment, etc. As a result of the sedimentary paleoenvironment (paleogeography). The different views on sedimentary paleoenvironment (paleogeography) have led other oil and gas companies to give up other promising fields. This simple example not only proves that lithofacies paleogeography and its mapping methods have a fundamental and critical guiding role in the pre-hydrocarbon industry studies and even further exploration and development processes, but also shows that Chinese sedimentologists have also been actively exploring ways to enhance the utility of lithofacies paleogeography (Mou et al. 2016b), i.e., to integrate sedimentary lithofacies paleogeography studies with mineral and energy resource prediction. This is also an important aspect of the study of lithofacies paleogeography in China. This is also a major feature and development trend of lithofacies paleogeography in China since the end of 1990s. Another main feature and development trend is to explore how to improve the isochronism, instantaneity and objectivity of lithofacies paleogeography research (Mou et al. 2016b). It should be said that since Vail (1977) combined sedimentary facies analysis with seismic data, introduced the concept of sequence and proposed the concept of isochronous stratigraphic framework, how to draw up the lithofacies paleogeographic maps of system tracts or related interfaces in different sequences, so as to more truly reflect the sedimentary evolution of sedimentary basins, and more objectively and dynamically reflect the filling sequence and historical changes of sedimentary basins (Mou et al. 1992; Mou 1993, Mou et al. 1999, 2016b; Ma et al. 2002, 2005; Ma and Cai 2006; Ma et al. 2009; Jiang et al. 2007; Hua and Zhang 2009), and finally, the relationship between them and mineral and energy resources (time and space, genetic mechanism) will be clarified more precisely, so as to better serve the mineral and energy industries, this has always been the goal of sedimentologists. In China, the instantaneous mapping method of stratigraphic sequences developed by Mou et al. (1992) was the pioneer and representative of this method. In these two works, not only the theory and methodology of stratigraphic paleogeography are discussed in-depth, but also the practice and application of this methodology are discussed. These works are closely related to oil and gas exploration, development and applications. The theory provides a fundamental basis for the sedimentary environment and spatial and temporal distribution of sediments, minerals and energy resources, while the preparation of medium- and large-scale stratigraphic paleogeographic maps at the basin scale guides the exploration and development of oil and gas and achieves practical results, reflecting its application value. Up to now, many sedimentologists have explored and expanded the study of stratigraphic paleogeography and more elaborate mapping methods and achieved a great deal of results, such as Deng et al. (1997) and Zheng et al. (2000, 2001, 2002, 2008, 2010b) have been trying to apply the relevant principles and methods to the study and prediction of terrestrial sedimentary environments. Ma et al. (2009) compiled and published a tectonically stratified lithofacies paleogeographic map of the South China.

Just like the research and development history of sedimentology and lithofacies paleogeography in foreign countries, the development history of China is also accompanied by the development of the mineral and energy industries. Every innovation in theory and related technical methods is closely related to the demand of mineral and energy industries. The development of the latter cannot be separated from the key guidance of the former.

In China, oil and gas sedimentology developed from lithofacies paleogeography has experienced the stage of learning from abroad to practice (1949–1970), the stage of enriching and perfecting oil and gas sedimentology theory (1970–1990), and the stage of production and practice of combining oil and gas sedimentology with stratigraphic stratigraphy, seismology, logging, experiment and new computer technology (after 1990) (Gu and Zhang 2003). Nowadays, from the perspective of basic research and theoretical innovation, although the paleogeographic research of the activity theory and the research on the distribution of oceans, seas and continents on the paleolatitude coordinates are still the goals that sedimentary geologists strive and pursue, they are also the goals of sedimentary paleogeography today. Frontier areas of research. However, in terms of its practical applicability, just as the development of sedimentology and lithofacies paleogeography has become more integrated, the development of paleogeography cannot ignore the needs of the people it serves and still needs to persist in exploring appropriate guiding ideas and mapping methods in order to better serve the mineral and energy resources industries that are closely related to our lives. In recent years, Mou and Xu (2010) put forward the idea of "structural control of basin, basin control of facies, facies control of oil and gas basic geological conditions", and made full reference to mineral and energy resources, comprehensive application of oil and gas geology and other disciplines, the compilation of the lithofacies and paleogeography Atlas of China (Ediacaran-silurian) (Mou et al. 2016b) is an attempt to integrate basic research, theoretical innovation and practical application and finally achieve better results. This is of great significance not only for the study of sedimentology and lithofacies paleogeography, but also for the research and exploration of energy and mineral resources.

In recent years, as shale gas has become a research hotspot in the field of energy, the concept of shale gas sedimentology has emerged. Organic-rich shale, as the host of shale gas reservoir development, has its unique petrological characteristics. Identifying different petrological features is the key to evaluating the formation conditions, in-situ gas content and resources of shale gas reservoirs (Yang et al. 2010). However, at present, most scholars at home and abroad have studied the content and type of organic carbon, maturity, mineral composition, fracture system, temperature and pressure, structural preservation conditions and other aspects and deeply studied the adsorption mechanism (Zhang et al. 2003; Jarvie et al. 2007; Travis et al. 2008; Nie et al. 2009a; Zou et al. 2010c, 2011a). However, the petrological characteristics, depositional environment and depositional model of the organic-rich mud shale developed in shale gas reservoirs are less involved, which in turn determine the material basis for the development of shale gas, and the basic geological characteristics of shale gas investigation are more important.

Work in fine-grained sedimentology and paleogeography, including mudstone and shale, dates back to the 1940s (Dapples and Rominger 1945), with an initial focus on macroenvironmental and lithofacies studies, such as submarine channels and lithography. Submarine fans (Dill et al. 1954; Sullwold and Harlod 1960), turbidity currents and turbidites (Kuenen 1950), tidal currents and tidal rocks (Straaten and Kuenen 1958) and mud in Salt Lake (Dellwig 1955) environments and wind dust deposition in marine environment (Radczewski 1939). In the 1970s and 1980s, research expanded into sedimentary petrology (Picard, 1971; Spears et al. 1980) and sedimentation modelling, creating models for deep-sea suspended sedimentation (Schubel and Carter 1984), turbidity and isobath sedimentation (Stow and Piper 1984), tidal current sedimentation (McCave 1971), explored the genesis of fine-grained sedimentation in terrestrial lake environments (McCave 1971), conducted experimental (Kranck 1980) and simulation studies (McCave and Swift 1976; Stow and Bowen 1978), analysed the mechanisms of fine-grained sedimentation (McCave 1984), noting modeling studies of organic-rich fine-grained sediments (Sageman et al. 1991). In the 1990s, people gradually paid attention to the study of fine-grained sedimentary microstructure (Hulbert 1991) and its controlling factors. With the rapid development of the unconventional oil and gas industry, especially since the beginning of the 21st Century, with the development of the shale gas industry dominated by the USA, the study of fine-grained sediments and tight facies has received renewed attention (Jia et al.

2014). At the same time, for shale gas, organic-rich shale deposition modeling and mechanism research has attracted much attention (Loucks and Ruppel 2007). Various genetic models have been established for source rocks, mainly including upwelling models (Sageman et al. 1991; Su et al. 2007; Li et al. 2008; Zhang 2015), oceanic hypoxia event model (Sageman et al. 1991; Cappellen and Ingall 1994; Erbacher et al. 2001; Su et al. 2007; Li et al. 2008; Zhang 2015), pelagic suspended sedimentary model (Stow and Tabrez 1998; Stow et al. 2000), Black Sea model (Wijsman et al. 2002), continental margin slope-basin model (Loucks and Ruppel 2007), shallow-water shelf models (Leckie et al. 1990; Egenhoff and Fishman 2013), peripheral foreland basin depositional models (Lehmann et al. 1995) and inland lake basin depositional models (Piasecki et al. 1990; Gilbert et al. 2012; Xu et al. 2015a, b). At present, most of the evaluation methods for shale gas reservoir source rocks adopt the inversion method, that is, using residual organic matter in strata to evaluate source rock. However, some scholars use the emerging geobiological theory to evaluate the source rocks by forward modeling (Xie et al. 2006; Yin et al. 2008; Wu 2012).

### 1.2.3 Application Status of Lithofacies Paleogeography in Shale Gas Industry

The development history and research status of global sedimentology and lithofacies paleogeography show that, on the one hand, the development of sedimentology and lithofacies paleogeography in the world is, to a certain extent, driven by the development and demand of the mineral and oil and gas industries. On the other hand, lithofacies paleogeography not only has important basic theoretical significance for humans to study the tectonic evolution history of the earth, the control of tectonic activity on the attributes of sedimentary basins, the restoration of ocean-continent patterns and the transformation of geological historical periods, etc. In the research of oil and gas resources, exploration and development, prospect prediction of sedimentary layer-controlled minerals, and water resources exploration also play a very critical role (Mou et al. 2016b). In layman's terms, different sedimentary systems and sedimentary facies control the most primitive exploitation conditions of mineral resources and oil and gas resources in the geosphere; that is, different paleoenvironment or paleogeography will form different mineral resources and oil and gas resources. The rule is summarized as "facies control oil and gas, basic geological conditions" (Mu and Xu 2010). Then, we should be able to preliminarily reveal the internal relationship between sedimentation and the distribution of energy and mineral resources through lithofacies paleogeography and mapping methods. If the knowledge from other disciplines is integrated on this basis, we will be able to reveal the causes of energy and mineral resources more deeply.

Therefore, it is concluded that lithofacies paleogeography is not only a theoretical guide to the study of mineral and energy resources, revealing their intrinsic connections, which has the property of 'guidance', but also its mapping method is itself a method for finding minerals and oil and gas, which can be directly applied to the exploration and development of mineral and energy resources (Mou et al. 2011, 2016b), which has the property of 'key technology'.

As early as 70 years ago, Mr. Xie Jiarong put forward the forward-looking view of paleogeography as a guide for prospecting work (Xie 2001). He was the first geologist to openly put forward paleogeography as a guide to prospecting. The first application of facies paleogeography and its mapping method in oil, gas and mineral exploration and development. Xie Jiarong (2001) proved the key role of paleogeographic interpretation by the discovery of new coalfields and coalfields in Huainan and considered that paleogeographic conditions controlled the physical and chemical properties of coal seams and the economic value of exploration and development. The distribution of bauxite and phosphate deposits is also controlled by paleogeography. He further pointed out that the exploration of copper and iron ore still needs a correct understanding of paleogeographic characteristics. Under the guidance of this theory, lithofacies paleogeography of different scales is a method to search for mineral resources such as coal seams, bauxite, phosphate rock, copper and iron ore. In addition, sedimentology, lithofacies paleogeography and its mapping methods have been playing a very important role in conventional oil and gas exploration (Feng and Wu 1988, Feng et al. 1991, 1994, 1997b, 1999, 2000; Mou et al. 1992, 1997b, 2000, 2010, 2011, 2014, 2016b; Tian and Wan 1993, 1994; Chen and Wang (1999), 2009a; Ma et al, 2002, 2005; Ma and Cai 2006; Ma et al. 2009). Tian and Wan (1993) guided by lithofacies paleogeography, studied the distribution, sequence and lithofacies of the Jurassic in China according to the Chinese tectonic environment, paleogeographic outline, sedimentary lithofacies and stratigraphic sequence characteristics and analyzed the hydrocarbon-bearing geological conditions of the Jurassic in China. Feng and Wu (1988) studied the petrology and lithofacies paleogeography of the Qinglong Group in the lower Yangtze region, and from the isopach map of dark rock group of the Qinglong Group, the distribution law of oil layers can be seen historically and comprehensively; Granular limestone formed in shoal environment, quasi-contemporaneous dolomite and limestone with structural cracks are all favorable oil and gas reservoirs; Marl can also be used as oil and gas caprock. He studied the hydrocarbon generation, storage and caprock conditions of the Qinglong Group from the perspective of lithofacies paleogeography. In his monograph "China Sedimentology", "Lithofacies Paleogeography and Jingbian Gas

Field", "Lithofacies Paleogeography and Hudson Oilfield in the Tarim Basin", "Lithofacies Paleogeography and the Hudson Oilfield in the Tarim Basin", "Reef Gas in the Upper Permian Changxing Formation in the Sichuan Basin" Reservoir exploration", "Lithofacies paleogeography research has led to a major breakthrough in the exploration of oolitic shoal gas reservoirs in the Feixianguan Formation in the Sichuan Basin", and "the important role of sedimentary facies in the breakthrough of oil and gas exploration in the Yanchang Formation", etc. The guiding role of geography or sedimentary facies in oil and gas exploration (Feng et al. 1991, 1994, 1997b, 1999, 2013), these are typical applications of quantitative lithofacies paleogeography and mapping (methods) in oil and gas exploration and development. Liu and Xu (1994) discussed the prospect of oil and gas by studying lithofacies paleogeography in Southern China, laying a foundation for the application of lithofacies paleogeography research and mapping (methods) in oil and gas exploration in Southern China. During the "Seventh Five-Year Plan" period, in the project of "Prospecting Foreground Prediction of Lithofacies Paleogeography, Sedimentation and Stratum Control in South China" presided by Academician Liu Baojun, Mou et al. (1992) used the theory and method of sequence stratigraphy to combine the Combined with this, the method of sequence lithofacies paleogeography was first proposed in China, and the ore-controlling mechanism of the sedimentary system tract was discussed by taking a Devonian sedimentary layer-controlled ore deposit in South China as an example. And, it is the first application of sequence stratigraphy in oil and gas minerals. In future research, it is further considered that "the division of sedimentary sequence sedimentary system tract and the compilation of the sequence lithofacies paleogeographic map can be used for the research and analysis of the spatial configuration of the oil and gas source-reservoir-cap rock", and it is pointed out that this method provides research ideas and working modes for "selection and evaluation from sequence stratigraphy-sequence lithofacies paleogeography-oil and gas source-reservoir-cap rock", and the Permian in Hunan, Hubei and Jiangxi are taken as the research objects to compile corresponding sequence sedimentary system. Geographical map, combined with the sedimentary characteristics of each system tract, analyzed horizontally and vertically and discussed the spatial configuration of oil and gas source-reservoir cap rocks in the Hunan-Hubei-Jiangxi region (Mou et al. 1992; Mou 1994; Mou et al. 1997b, 2000). Guidance and application of facies paleogeography [especially sequence lithofacies paleogeography and its mapping (methods)] in the oil and gas geological survey in the Hunan, Hubei and Jiangxi regions. The idea and method of applying lithofacies paleogeography theory, lithofacies paleogeography or sequence lithofacies paleogeography has been widely studied and applied in national oil and gas geological surveys and even used to guide oil and gas (Mou et al. 1992; Mou 1994; Mou et al. 1997b, 1999, 2007, 2010, 2011, 2014; Xu et al. 1994; Mei et al. 1996, 2005, 2006, 2007; Li et al. 1998; Chen and Wang 1999, 2000, Chen and Ni (2005), 2009; Tian et al. 1999, 2000, 2008, 2010; Zheng et al. 2000, 2001, 2002, 2009; Ma and Cai 2006; Ma and Chu 2008; Zhou et al. 2006; Wang et al. 2007, Zhu et al. 2008; Lu and Ji 2013). The most typical application is the discovery of the Puguang gas field in the Sichuan Basin. Ma et al. (2010) believed that the innovation of geological knowledge, explore ideas and exploration technology had brought about the discovery of the Puguang gas field. The main contribution of the distribution pattern of salt rock reservoirs is the study of lithofacies and paleogeography and the compilation of related maps. On the basis of detailed analysis of the sedimentary characteristics of the depositional system of the Permian Changxing Formation, the time and the spatial distribution of each sedimentary facies belt were defined, and the corresponding lithofacies paleogeographic maps were compiled. It is believed that the reefs of the Changxing Formation are reefs on the gentle slopes of the carbonate platform margins, which are intermittently distributed along the platform margins. It is pointed out that the shoals and reefs on the platform margin. It is the most favorable facies belt for oil and gas reservoirs, and reef dolomite and granular dolomite are the most favorable microfacies for reservoirs (Mou et al. 2016b). In fact, the reef gas reservoir of Changxing Formation in the upper Permian in the Sichuan Basin has experienced a difficult geological survey and exploration process. During this process, under the misleading of two wrong geological understandings, the exploration of the reef gas reservoirs at that time was stagnant (Feng et al. 2008). To make a breakthrough, it is necessary to re-understand the genesis of reef gas reservoirs (shoals and reefs at the edge of the platform) and geological distribution patterns (lithofacies and paleogeographic features). By studying the characteristics of reefs and reef gas reservoirs, it is considered that reef gas reservoirs are obviously controlled by lithofacies paleogeography and sedimentary facies belt, and lithofacies paleogeography controls the distribution of reefs and reef gas reservoirs. The exploration success rate of reef gas reservoirs in the Changxing Formation of Upper Permian in the Sichuan Basin has been improved, and a major breakthrough has been made in reef gas reservoir exploration (Feng et al. 1997a, b, 1999, 2013; Mou et al. 2003, 2005; Ma et al. 2002, 2006, 2007, 2010, 2014).

In a word, the theoretical development of lithofacies paleogeography and the progress of related technologies, such as the innovation and development of mapping technology of sequence lithofacies paleogeography, have played an important role in the geological investigation and exploration and development of sedimentary minerals and conventional oil and gas resources in the past decade. It plays a very important role in developing new oil exploration fields such as rivers, deltas and slump turbidite fans, deep-water gravity flow deposits, beach bars, reefs and carbonate uplifts and promoting the exploration and development of oil and gas resources. It has played an irreplaceable role in theoretical guidance (Zhu 2008) and is a key technical method.

Shale gas reservoirs are a kind of oil and gas resource. However, the guiding role of lithofacies paleogeography theory and mapping methods in shale gas geological survey and exploration and development, as well as the status of key technologies and methods, have not been fully understood. Geological survey, exploration and development of shale gas in China have made remarkable achievements in a short time, but it is still in the initial stage. It is moving from theoretical research to practice, from investigation in key fields to multi-field and multi-type evaluation and from local experiments to scale investment. Originally, the research work on shale gas geology in China has drawn on the experience of the USA from the very beginning, while the geological conditions of shale gas in the USA are relatively simple and its basic research work is relatively maturity, thus the basic geological background such as lithofacies paleogeography distribution and mapping methods in shale gas geological survey and exploration and development of the application of less attention and research.

It is considered that through basic geological research (such as sedimentary facies, lithofacies and paleogeography) and the determination of source rocks, especially the determination of high-quality source rocks, the potential of oil and gas resources in petroliferous basins can be scientifically evaluated, and the generation, migration and migration of oil and gas can be deeply recognized. The laws of migration, aggregation and enrichment are of great significance (Lu et al. 2006; Hou et al. 2008; Zhang et al. 2010a, b). Among them, the shale gas reservoir with the integration of source and reservoir is especially true, and it is particularly important to study its material basis and controlling factors in depth. As mentioned earlier, predecessors have done some research on the sedimentary model and enrichment mechanism of shale gas reservoir source rocks and achieved some results. However, the research on the relationship between source-reservoir allocation, favorable sedimentary environment and main controlling factors of source rocks is still insufficient, especially the application of sedimentology and lithofacies paleogeography in shale gas has not been studied. Fortunately, they have already participated in it: Liang et al. (2011) studied the influence of the Niutitang Formation depositional environment on the enrichment of organic matter in Northern Guizhou and analyzed the Wufeng and Longmaxi Formations through electron microscope observation and mineral content analysis. The mineralogy, lithofacies and storage space types of the shale in this group were discussed, and the controlling factors for the performance of related shale reservoirs were discussed. Many factors control the distribution of the hydrocarbon source rock (Huang 2011), such as the paleoclimate, paleostructure, paleoenvironments, it is impartial to put forward that "anoxic conditions" alone is the main control factor for effective source rocks, and "paleoproductivity" has a good correlation with organic-rich marine source rocks. As for the formation environment of source rocks, the high organic matter productivity of surface water is more important than the anoxic environment of bottom water. As long as the organic matter productivity is high enough, source rocks can also be formed in an oxygen-containing non-reducing environment. Gao et al. (2012) studied the shale of the Sargan Formation and the shale of the Yingan Formation in the Tarim Basin and concluded that the organic matter content and density of the source rocks of the two groups are consistent with the rise and fall of sea level. Corresponding relationship, all have the characteristics of sea-level rise, organic matter abundance increase, mud shale density decrease, and sea-level decrease, organic matter abundance decrease and mudstone density increase. And, it is pointed out that the sea level change is influenced by the comprehensive control of tectonic activities and changes in the sedimentary environment. Xie et al. (2015) further analyzed the biological composition and organic carbon content according to the idea of depositional environment-biological composition-source rock formation, and then discussed the relationship between depositional environment and source rock development and concluded that the former absolutely controls the latter. Lin et al. (2015) also believed that the structure and paleoclimate can control the formation and disappearance of the accommodation space, and the supply of water and sediments, the products of the sedimentary environment, affects the development and evolution of the basin and also affects the physical and chemical properties of sedimentary water bodies. These properties and biological development ultimately control the development characteristics of source rocks by influencing preservation conditions, paleoproductivity and sedimentation rate. In a word, the source rock is the material base of shale gas exploration, and its forming environment and its control on the sedimentological characteristics and processes of the formation and preservation of the source rock are studied. It is of great significance to the shale gas geological survey and further exploration and development in the future and deserves the attention of many shale gas researchers.

In the research on the characteristics of shale gas reservoirs, most of the predecessors studied shale as a source rock, but relatively few studied it as a reservoir rock. In North America, significant progress has been made in the study of shale gas pore characteristics by studying the microscopic characteristics of shale reservoirs represented by micron-scale and nano-scale microporosity, which plays an important role in guiding the exploration and development of shale gas. In China, Zou et al. (2010b) discovered nano-scale pores in mud shale for the first time through nano-CT technology, which opened the prelude to the research on nano-scale pores in oil and gas reservoirs. The same is true for shale gas reservoirs. Many scholars have studied the characteristics, types and forming conditions of shale reservoirs and put forward the evaluation parameters for shale reservoirs (Curtis 2002; Jiang et al. 2010; Zou et al. 2010b; Guo et al. 2011). Because of the importance of shale gas reservoir characteristics, the study of its controlling factors has been paid more and more attention. The study found that there is a close relationship between sedimentary (micro)facies and shale reservoir lithofacies, characteristics, reservoir properties and distribution, etc. However, is this relationship a positive correlation under any conditions? It is still a positive correlation under certain conditions, or even a negative correlation, and there is no clear conclusion yet. Relevant research is being carried out gradually, and many researchers have begun to work in this area in the past two years. For example, Guo et al. (2015) studied the shale reservoir rocks of the Shanxi Formation through parameters such as logging data, logging data, core observation description, thin section analysis, particle size analysis, X-ray diffraction whole-rock analysis and total organic carbon content. And, the sedimentary microfacies controlling the distribution of shale reservoirs in the Shanxi Formation are described in detail by facies and sedimentary microfacies types. Through the study of lithofacies paleogeography and mapping technology, the spatial distribution law of favorable sedimentary microfacies is recognized. Application of lithofacies and paleogeography research and mapping in shale gas geological survey and in-depth study of reservoirs. Xu et al. (2015a, b) also conducted a comprehensive analysis and research on the reservoir characteristics of shale formations in the central and Southeastern Hunan depression by using X-ray diffraction, scanning electron microscopy and isothermal adsorption technology under the background of regional deposition. It is another practice of lithofacies paleogeography in shale gas geological investigation and in-depth study to study the distribution of favorable reservoirs by geographic mapping.

To sum up, the conventional oil and gas geological survey and exploration and development practice in China for decades, as well as the shale gas geological survey and exploration and development practice in recent decades, show that the distribution of source rocks in China, that is, the sedimentary environment of the potential shale gas distribution area and the later multi-stage structural transformation, has not been systematically studied up to now. The relationship between organic geochemical parameters (organic carbon content, type of organic matter, thermal evolution degree of organic matter, etc.) and mineral composition of source rocks and tectonic background, sedimentary environment and paleogeographic distribution has not been systematically or fully studied in China, and only a few reports are available (Li et al. 2013a, b; Wang et al. 2013; Wang (2015)). Sedimentology and lithofacies paleogeography are the theoretical guidance for shale gas geological survey, and lithofacies paleogeography mapping technology is the key technology to optimize shale gas prospect areas, favorable areas and target areas. The related theories, methods and technologies have not been systematically developed. Mou et al. (2016a) discussed the role of lithofacies paleogeography and its mapping method in shale gas survey in relation to the study of shale gas in the Longmaxi Formation in Southern Sichuan Basin and adjacent areas, it is the first time that the study of lithofacies paleogeography can be used as a guide and a key technical method for shale gas geological survey. In fact, in the face of extremely complex geological conditions of shale gas in China, the extensive and relatively lagging theoretical research on shale gas geology and the weak research foundation, in the geological survey of shale gas in China, attention should be paid to the research of key technologies and methods of basic geology and geological survey, and the main research directions should be the research of source rock lithofacies paleogeography, mapping method and key technologies and methods of geological survey. The practice of shale gas exploration and development in China also proves that lithofacies paleogeography controls the combination of basic elements of shale gas accumulation and the distribution of shale gas resources. It is necessary to strengthen the study on the controlling effect of sedimentation on the distribution law of shale section, that is, source rocks. It is necessary to strengthen the superposition of multi-information, multi-scale, diversified and digitized paleogeography and shale gas geological conditions parameters based on mapping and explore the methods of optimizing the prospect, favorable area and target areas.

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