3 Shale Gas Geological Survey

Abstract

It is clearly proposed that “lithofacies paleogeography can be used as a guide for shale gas geological survey work”. Lithofacies paleogeography is not only the theoretical guidance of shale gas geological survey work, but also its related mapping technology method is the key method to “find” shale gas.

Keywords

Constituency evaluation • Working methods • Shale gas • Geological survey • Lithofacies paleogeography

3.1 The Task of Shale Gas Geological Survey

In recent years, China's consumption and production of conventional energy fuels have reached a record high level. Oil and natural gas still dominate the energy consumption structure. The sharp rise in domestic unconventional oil and gas production has basically balanced domestic oil and gas supply and demand (Jia et al. 2014). However, in the production of unconventional oil and gas resources, relatively cleaner shale gas resources have little contribution to the production, which is inconsistent with China's huge potential status of shale gas. Compared with the unconventional resources such as tight gas and coalbed methane that have achieved large-scale industrial production, the large-scale production of shale gas has made relatively slow progress, so it is necessary to seek further to realize the large-scale and effective development of shale gas resources.

Shale gas, as retained gas in source rocks (Li et al. 2012) and residual gas (Mou et al. 2016), is the accumulation of oil and gas in source rocks. In China, there are huge differences in the research basis and degree between petroliferous basins and sedimentary areas outside of petroliferous basins or where the degree of oil and gas exploration is very low. The former may have a certain working basis for basic data such as gas-bearing shale development series (including shale distribution and thickness), organic matter content and type, thermal evolution degree, gas display, rock characteristics and mineral components of gas-bearing shale.

However, for the latter, the above basic information is relatively lacking. In view of the research status in China, such as large differences in the basic work related to source rock research, weak foundation, no system, no detail and late start of research as shale gas, it is necessary to clarify its main tasks before the large-scale geological survey of shale gas.

Based on the author’s own actual experience in shale gas geological survey, combined with the analysis of domestic shale gas research status, existing problems and research trends, it is concluded that China’s shale gas geological survey has three basic and main tasks at present:

(1) Clarify the basic geological characteristics of source rocks, including lithologic characteristics, sedimentary environment, sedimentary microfacies (rock) types and characteristics, organic matter types and contents, mineral composition, etc. Mainly through core and field observation and relevant sampling work, carry out the analysis of lithologic characteristics, depositional environment and TOC and Ro of shale of source rock and clarify the types and content of organic matter in source rocks. Further, analyze the types and contents of conventional minerals and clay minerals in source rocks, summarize the conventional mineral composition of source rocks and the variation law of clay mineral composition in the section and comprehensively study the basic geological characteristics of source rocks.

(2) Clarify the temporal and spatial distribution law of source rocks, including their thickness, buried depth, fine distribution, area, etc. Mainly through the field, combined with seismic and drilling data, the distribution range and distribution law of source rocks are

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studied, and their thickness variation law, buried depth and variation trend are analyzed.

(3) Optimize the prospective area and favorable area of shale gas reservoir. After completing tasks (1) and (2), we have the basic conditions to carry out the optimization of shale gas scenic spots and even favorable areas. On the basis of clarifying the scope of shale gas scenic spots, we can further carry out the research on the gas-bearing property of source rocks, reservoir capacity and resource potential analysis and select appropriate parameters in combination with geochemical indicators to further optimize the favorable areas or even dessert areas of shale gas.

3.2 Methods of Shale Gas Geological Survey

At present, China's shale gas geological research is in the stage of rapid development. Local exploration units represented by China Geological Survey are carrying out large-scale shale gas geological surveys, moving from theoretical learning to scientific practice, from key area survey to multi-regional and multi-type evaluation and from local test to large-scale investment. However, the geological conditions of shale gas in China are extremely complex, the theoretical research of shale gas geology is extensive, there are many problems, and the theoretical research is relatively backward. Combined with the basic purpose and task analysis of shale gas geological survey, the author believes that in addition to the guidance of basic geological theory, the key problem is to select appropriate technical methods.

In oil and gas exploration, although different disciplines have played different roles in identifying or making oil and gas breakthroughs, in the early stage of oil and gas exploration, lithofacies paleogeography research is indispensable and one of the key foundations for making breakthroughs in oil and gas resources. It is also a method of oil and gas exploration (Mou et al. 2010, 2011), and the same is true for shale gas (Mou et al. 2016).

At present, the mainstream view on the formation of oil and gas (including shale gas) is still the theory of organic genesis (Wang et al. 2003). Therefore, the formation of oil and gas is closely related to lithofacies paleogeographic environment from the generation and development of primitive organic life to the later death, burial, decomposition and migration and from the material of oil and gas reservoir to the formation of its preservation body. For shale gas, the study and reconstruction of lithofacies paleogeography can help clarify the scientific problems related to its occurrence carrier—organic-rich shale. Faced with shale, a restricted area of oil and gas exploration in the past, it is difficult to evaluate the target area of shale gas exploration, and the exploration risk and cost are high. Therefore, the understanding of lithofacies and paleogeography of shale gas target area has become more important, which should be paid attention to by geological investigators. However, oil and gas geologists and sedimentary geologists who conduct geological investigation and research on shale gas pay more attention to the geological characteristics of shale gas carriers (organic-rich shale), such as TOC, Ro, mineral composition. Secondly, it pays attention to the structural preservation conditions similar to conventional oil and gas reservoirs; however, the basic research on the fine sedimentary environment for the development of organic-rich shale, the carrier of shale gas and the research on the optimization of prospective area, favorable area and target area of shale gas as a key method is relatively few. A large number of studies show that the sedimentary environment not only controls the thickness, distribution area and organic carbon content of organic-rich shale, but also determines the sedimentary rocks type and mineral composition of the rocks, and the difference between rocks type and mineral composition determines the characteristics of physical property development of source rocks reservoir and then affects the accumulation of shale gas. Therefore, the sedimentary environment is the fundamental factor determining shale gas accumulation. Therefore, based on the study of regional sedimentary facies, the temporal and spatial distribution of favorable facies zones of source rocks can be clarified through lithofacies paleogeography mapping, so as to provide the basis and direction for shale gas exploration (Mou et al. 2016). For the basic geological survey of shale gas, the research on the sedimentology and lithofacies paleogeography of shale gas source rocks and reservoir and taking this as a method to delineate the scenic spots, favorable areas and target areas should be the eternal theme throughout the whole geological survey of shale gas and the process of further exploration and development. In fact, the fundamental goal of a shale gas geological survey is to find prospective areas and favorable areas of shale gas, so as to provide a scientific basis for shale gas exploration and development (Mou et al. 2016). Therefore, the theory and method of "using superposition method to evaluate the prospective area, favorable area and target area of shale gas based on the mapping research and mapping of lithofacies paleogeography" should be the key technical method of large-scale shale gas geological survey. Research and practice have proved that the research and mapping of lithofacies paleogeography can be used as the basic method and key technology and can guide the geological survey of shale gas.

3.2.1 Sedimentary Basin and Shale Gas

A large number of studies show that sedimentary basins play the most basic and important role in controlling the occurrence of a variety of sedimentary minerals and oil and gas (Wang and Li 2003), and the formation of sedimentary basins is controlled by tectonic activities and evolution. Zhang et al. (1991) pointed out that the three Chinese mainland plates were affected by China's three tectonic cycles during the geological history, including the splitting, drifting, collision and convergence of China's continental tectonic cycle. These tectonic activities control the evolution of petroliferous basins and lithofacies paleogeography in China and the evolution of the types of petroliferous basins in China from generation to generation and then control the distribution of oil and gas. The idea of activity theory and stage theory runs through the book lithofacies paleogeography and oil and gas in China's petroliferous basins. Academician Tian (1997) believes that paleogeography and its changes are mainly controlled by the degree of crustal differentiation and plate tectonic evolution, and the types of sedimentary basins are controlled by tectonic action (Tian and Zhang 1997), which further controls the distribution of paleogeography and the generation of oil and gas. In fact, with the advent of the theory of plate tectonics, people gradually realized that the formation of sedimentary basins is closely related to mantle material activities and is controlled by the tectonic system (movement); structure plays an important role in controlling the formation, evolution and sedimentary sequence of sedimentary basins and then affects the distribution of oil and gas (Wang et al. 1985; Liu and Xu 1994; Mou et al. 1999, 2010, 2011; Wang and Li 2003). For example, Mou et al. (2010, 2011) analyzed from the structural point of view and believed that today's South China could be divided into the Yangtze Block and Cathaysian Block. From the Cryogenian (Nanhua period), due to the influence of basement properties and tectonic activities, the sedimentary evolution of South China has been differentiated. There are different sedimentary environments and sedimentary filling sequences in the Yangtze area and Cathaysian Block. The main type of sedimentary basin in South China belongs to the Craton Basin. Most of its periods are epicontinental sea and limited shallow sea environment, which constructs stable carbonate platform sedimentation and widely distributed black shale sedimentation. The Cathaysian Block is in an active tectonic environment with strong volcanic activity in the early stage. The sedimentary basin type belongs to the rift basin. There is no unified carbonate platform deposition, and the main body is terrigenous clastic deposition and filling. The different tectonic activities determine different types of sedimentary basins, further determine their different sedimentary environments and sequences and finally determine the different basic geological conditions of oil and gas in the two regions: The Yangtze region has rich source rocks, good reservoirs and sealing layers, while the Cathaysian Block has bad source rocks and reservoirs. Some scholars also believe that tectonic activity and tectonic pattern directly control the lithofacies paleogeographic environment and sedimentary system, determine the distribution of sedimentary areas and provenance areas, sedimentation, changes in sedimentary environment and paleogeography and often affect the changes in climate environment (Jing et al. 2012). In fact, the above laws can be summarized as that the structure controls the formation of the basin. The basin is the accumulation space of materials. Therefore, the structure determines the sedimentary filling sequence and sedimentary style of the basin and finally determines the original basic geological conditions and combinations of oil and gas, that is, "basic geological conditions of structure controlling basin, basin controlling facies and facies controlling oil and gas" (Mou et al. 2010). In the field of petroleum geology, many scholars have always advocated the epistemological view that "structure is dominant, sedimentation is the foundation, oil generation is the key, and transportation, accumulation, and preservation are the conditions". Therefore, the analysis of prototype sedimentary basin types and the study of detailed sedimentary characteristics and evolution sequences under their control is the basis for analyzing basic geological conditions of oil and gas. Shale gas is no exception.

For shale gas reservoirs, although they are different from conventional oil and gas reservoirs and do not need structural traps, shale gas may be formed as long as there is a place where organic shale is developed (with space for accumulation of organic shale). That is, to some extent, shale gas may be formed in any sedimentary basin as long as there is organic-rich shale (Wu et al. 2013). Based on the author's understanding and definition of shale gas, organic-rich shale, as the filling sequence and sedimentary style (or one) of these sedimentary basins, it is also the most primitive and basic material basis for the formation of shale gas. Therefore, in the geological survey of shale gas, the first thing to do is to find the places where these primitive and basic material bases are accumulated, find favorable structural units and judge whether it is a "complete shale basin" conducive to the development of organic shale, to analyze the prototype sedimentary basin type of organic shale, restore the complete shale basin rich in organic shale as much as possible and, on this basis, screen the structural sedimentary units conducive to the development of shale gas reservoirs, such as the stable Craton Basins (generally conducive to the development of biogas) and the Foreland Basin (generally, the basin with relatively developed conventional oil and gas is also conducive to the development of shale gas reservoir of thermogenic gas type). Among those "fragmented" sedimentary basins, such as some inter-arc basins, pre-arc basins and back-arc basins with volcanic rocks under the background of tectonic compression, although mud shale will also develop and be source rocks and full of "residual gas" to form shale gas, but due to the influence of factors such as the area, thickness and capping layer of shale gas source rock (they are the influencing factors of shale gas reservoir enrichment), shale gas reservoirs with industrial development value are often not formed.

Theoretically, from the time scale, the sedimentary basin should be a syngenetic sedimentary basin. However, it is undeniable that due to the control of tectonic, the deformation of sedimentary basins during and after deposition and the superposition of different types of structures in the later stage, there may be a great controversy on the understanding of basin types in the original organic shale-rich sedimentary period; from the perspective of sedimentary basin analysis, the formation, development and extinction of a specific basin are a quasi-continuous evolution process, and the superimposed basin has nothing to do with the basin formed in the specific period and specific dynamic mechanism studied (i.e., the prototype basin in the development and sedimentation period of organic-rich shale). The prototype sedimentary basin can be the basis or basement of the later basin and even determine various elements of the later basin to varying degrees; the late basin has no effect on the formation and evolution of the early basin. It plays a role in the transformation of the early basin, and the fundamental reason for this transformation is the transformation of the dynamic mechanism. The research shows that no basin has crossed the whole Phanerozoic and no region, and the basin type has not changed since ancient times. Therefore, the practice of dividing all sedimentary strata in a certain area into one basin and taking successive basins formed under different dynamic mechanisms as different stages of a basin is contrary to objective facts and geological principles (Wang and Li 2003).

Gong et al. (2012) analyzed and compared the reservoir forming conditions of shale gas reservoirs in the USA, especially the control of structures and sedimentary basin types under their control of shale gas reservoir forming conditions and considered that the Foreland Basins are favorable places for shale gas formation and accumulation. The reason is that the lower strata of the Foreland Basin are usually stable craton shale deposits rich in organic matter, which provides sufficient material basis for the formation of shale gas. The upper strata of the Foreland Basin experienced multi-stage thrust folds, and the resulting tectonic thermal events provided thermal and dynamic conditions for the maturity of the lower source rocks and the generation of natural fractures, making the Foreland Basin an ideal place for shale gas accumulation. Li et al. (2013) also pointed out that the research about the control effect of structure on the distribution law of gas-bearing shale should be strengthened by analyzing the research status and problems faced by domestic shale gas. In other words, it is also the research on the type of prototype sedimentary basin. Shale gas reservoirs have the basic characteristics of integration of source and reservoir. Research shows that relatively high-quality reservoirs are often formed in a specific period with a small span, and the thickness may be only a few meters. For example, the most high-quality source rocks and shale gas development interval of the Fuling shale gas field of the Wufeng Formation-Longmaxi Formations at its bottom (Guo 2016), which is the first large shale gas field in China, and its material composition and lithofacies environment are significantly different from the similar lithology underlying and overlying it. What makes this obvious difference must be that there are some mechanism working. If we can accurately restore the types of sedimentary basins which controlled by structural evolution, clarify the distribution law of sediment filling process and lithofacies environment development under its control and master the internal law between them, it is possible to characterize the fine organic-rich shale section of shale gas development. This process is actually the analysis of sedimentary basins. Of course, it also has the analysis of fine sedimentary facies under its control, which will be discussed in detail below. In addition, in the process of analyzing the type of prototype sedimentary basin, we will have a very in-depth understanding and understanding of the geological background of the development of source rocks (such as the development degree of existing faults and microfractures, development characteristics of caprock, hydrogeological conditions, current pressure conditions), which will help to solve the research problems of shale gas preservation conditions. This is a great significance for the research on the important scientific problem of shale gas exploration and development, but it is not a high status in the research of shale gas preservation conditions in China.

The ultimate goal of the shale gas geological survey is to find shale gas reservoirs with industrial exploration and development value. Research and practice show that shale gas reservoirs with exploration and development value often exist in (or develop in) complete sedimentary basins. Most of those that have realized shale gas development or have great shale gas potential are Foreland Basins and the Craton Basins. Taking the USA as an example, nearly 20 shale gas blocks found in its 48 states widely develop gas-bearing black shale, most of which are developed in the Craton Basins and the Foreland Basins, such as the currently exploited shale gas reservoirs in the Foreland Basin on the west side of Appalachian-Quachita in the Eastern USA and the back-uplift basin group. At the same time, its potential shale gas blocks are also mainly distributed in the Foreland Basins and back-uplift basin on the east side of Rocky

Mountain (USGS 2013). The tectonic evolution of the main development stages of these two sedimentary basins types and the paleogeographic conditions under their control, such as an anoxic reduction environment, suitable hydrodynamic conditions and less supply of terrigenous debris in most layers, control the formation of high-quality source rocks and shale gas with different genesis and maturity (Li et al. 2009). In China, taking the marine shale gas in Southern China as an example, the research shows a very large shale gas prospect in Sichuan Basin. The main development horizons are the Cambrian Niutitang Formation developed in the Craton Basin and the Late Ordovician Wufeng Formation-Early Silurian Longmaxi Formation in the back-uplift basin (Mou et al. 2010, 2011; Ge et al. 2014; Liang et al., 2014; Zhou et al. 2015) (Fig. 3.1). Or most researchers believe that the type of sedimentary basin is a Foreland Basin in the Late Ordovician-Early Silurian period formed on the eastern margin of the Yangtze Block due to the convergence of the Yangtze Block and the Cathaysian Block (Wang 1985; Liu et al. 1993; Xu et al. 1996; Yin et al. 2001, 2002; Su et al. 2007; Wang et al. 2012a, b, c, d; Wang et al. 2012a, b, c, d). In the Dabashan area on the northern edge of the Yangtze plate (the transition between the south side and the Sichuan Basin), the fracturing yield of shale gas in the Jurassic Zhenzhuchong section of well Yuanba 9 on Northeast Sichuan exceeds 1×10^4 m^3, Jiannan 111 well. After fracturing, the daily natural gas production in the Dongyuemiao section is 3000 m^3. The geological survey and exploration and development of shale gas in organic shale-rich strata have made a preliminary breakthrough (He and Zhu 2012). Further analysis also shows that the maximum thickness area of organic-rich shale in the Lower Jurassic Ziliujing Formation is distributed in the front of the Dabashan orogenic belt and controlled by the tectonic activity and tectonic load of the Dabashan orogenic belt, while the tectonic activity of Longmenshan orogenic belt is relatively weak and has little impact on its sedimentary and sedimentation. They all have a complete orogenic belt Foreland Basins system. At the western edge of the North China plate, in April 2011, the gas was produced by shale gas fracturing test of Chang 7 section of Liuping 177 well. The depth of the vertical well is 1000–2000 m, and the test output of shale gas is generally 1500–2000 m^3 [Li et al. 2015 (internal meeting data)], which is the first continental shale gas well in China. The study shows that the western margin of the Ordos Basin was a Foreland Basin in the Late Triassic, and the basement has the nature of a Craton Basin. These relatively stable tectonic backgrounds and the types of favorable sedimentary basins under their control have laid a favorable sedimentary environment for the development of source rocks and are the decisive factor for the enrichment of shale gas reservoirs.

In addition, the sedimentary pattern of the South China Basin is very different from the Mesozoic, and the sedimentary mechanism of the South China Basin is very different. Moreover, the sedimentary mechanism of the South

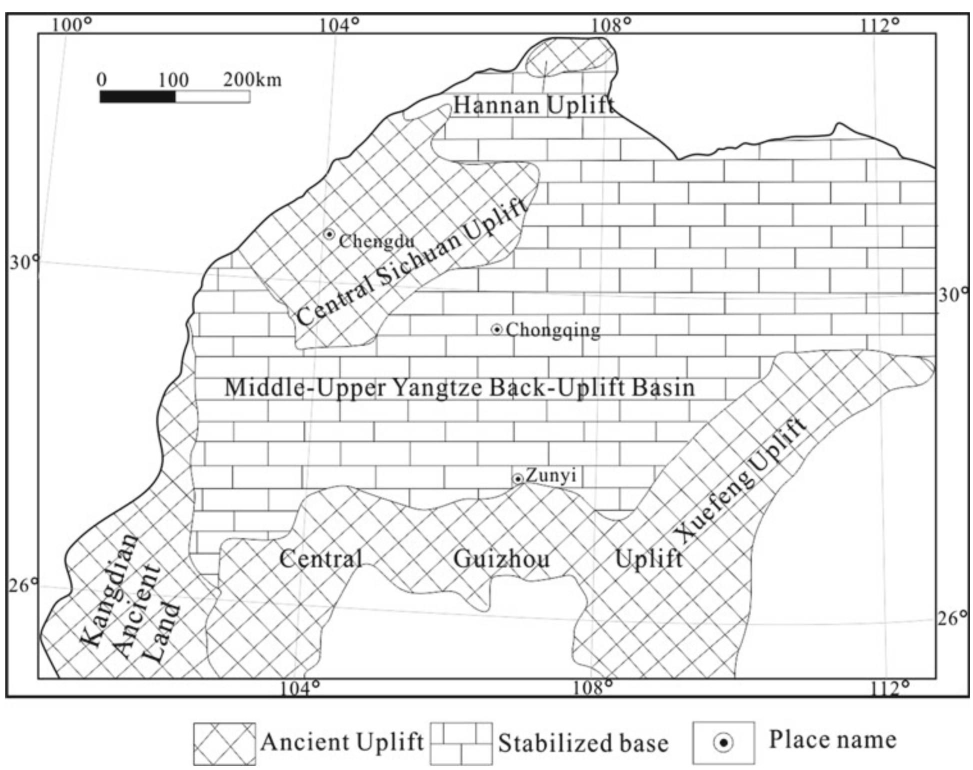

Fig. 3.1 Distribution of Late Ordovician-Early Silurian tectonic framework and sedimentary basin types in the Middle-Upper Yangtze region (modified by Mou et al. 2010, 2016)

China Basin is very different from the Mesozoic, and there are many tectonic changes. In the Mesozoic and even the Paleozoic, the basin experienced great tectonic deformation. The South China Basin has experienced tectonic uplift and Paleozoic, and the tectonic stability is very different. The sedimentary environment, tectonic setting and preservation conditions are extremely complex (Mou et al. 2010, 2011, 2016). The above factors have brought great difficulties to find relatively stable and well-preserved shale zones, which is the basic task of shale gas geological survey and the key to exploration and development in China. From the perspective of theory and practice, whether there is a complete shale gas basin is very important for shale gas development. Therefore, in the process of actual geological survey and exploration, development and production, it is very necessary to reconstruct a complete and fine prototype sedimentary basin of shale gas development in combination with the structural background. It is necessary to study the nature of the sedimentary basin, the size, shape, scale, etc. This work affects the work deployment of shale gas geological survey, and the calculation of shale gas resources and reserves, and further affects the exploration and development of shale gas. In the process of shale gas geological survey, even in the face of the basin that has been strongly transformed, on the one hand, we should study its evolution history and trace the prototype of the basin from the perspective of geological history evolution; on the other hand, from the perspective of "tectonic basin control", we must study the plate tectonic background of the basin and the dynamic mechanism determined by it, so as to objectively and historically identify the basin type, so as to restore the complete sedimentary basin type in the development period of organic shale-rich shale conducive to the formation of shale gas.

3.2.2 Sedimentary Facies (Environment) and Shale Gas

The history of shale gas research and exploration practice in the USA for hundreds of years shows that one of the reasons why organic-rich shale in North America can make a major breakthrough in shale gas is that favorable sedimentary facies zones are generally developed. Although the mining area is small, it is in a favorable deep-water sedimentary environment. In addition, the favorable anoxic and stagnant sub-environment, which can be explained by the "Black Sea" detention quiet sea model and coastal upwelling model, has basically laid the foundation for the rich organic shale in its mining area and the high abundance of organic matter. Thicker thickness is a good material basis for shale gas development (Montgomery et al. 2005; Martineau 2007; Loucks and Ruppel 2007; Zhang et al. 2008a, b; Zou et al. 2010, 2013; Guo et al. 2012; Ma et al. 2012; Wang et al. 2012a, b, c, d; Li et al. 2013; Wu et al. 2013; Mou et al. 2016). They are the main factors for shale gas accumulation.

It is generally believed that in the deep-water slope and basin environment: first, organisms are relatively prosperous, which provides a rich material basis for oil and gas production and is conducive to the formation of a large amount of organic matter; second, except for the short-term strong hydrodynamic conditions in some areas during the turbidity current excitation period, the hydrodynamic conditions in most other sedimentary areas are generally weak, which are relatively quiet semi-deep water to deep-water low-energy environment, which is conducive to the development of source rocks and the preservation and transformation of organic matter. For example, in the development of black shale (source rocks) in Sichuan Basin and its surrounding, the Datangpo Formation is obviously controlled by the evolution of the rift basin: black rock series developed in areas with strong rifting or depression; from the center to the edge, the thickness of source rocks of Datangpo Formation gradually becomes thinner, and the content of organic matter gradually decreases (Fig. 3.2). Therefore, in the deep-water slope and basin environment, it is a favorable oil and gas generation area (Feng et al. 1997), which is also a favorable shale gas development area. It is concluded that the development and accumulation of shale gas are mainly controlled by the sedimentary environment.

In fact, unlike conventional oil and gas accumulation and distribution mainly controlled by the comprehensive control of "source, reservoir, cap, circle, transportation and protection", shale gas is a key reservoir forming system element such as source rock, reservoir and even caprock. In the same organic-rich shale rock series, the lithofacies type, development thickness, distribution area, organic matter type and content, maturity and other geochemical parameters, porosity and other physical parameters of its source rock influence the shale gas-rich integrated reservoirs. In terms of the industrial accumulation and exploration and development conditions of shale gas, the first thing we need is a rich gas source material basis, that is, high-quality source rock. The hydrocarbon generation conditions are required to meet certain standards, such as the large thickness of dark shale, good type of organic matter, high content of organic carbon, appropriate maturity and content of mineral components. This has been discussed earlier. Combined with the re-understanding of the definition of shale gas and the understanding of its development and distribution characteristics in this book, it is considered that the basic characteristics of the development of these source rocks, that is, the control factors affecting the rich accumulation of shale gas, are obviously controlled by sedimentary facies belts and their changes in plane and space (vertical and horizontal direction), and the development of organic-rich shale is

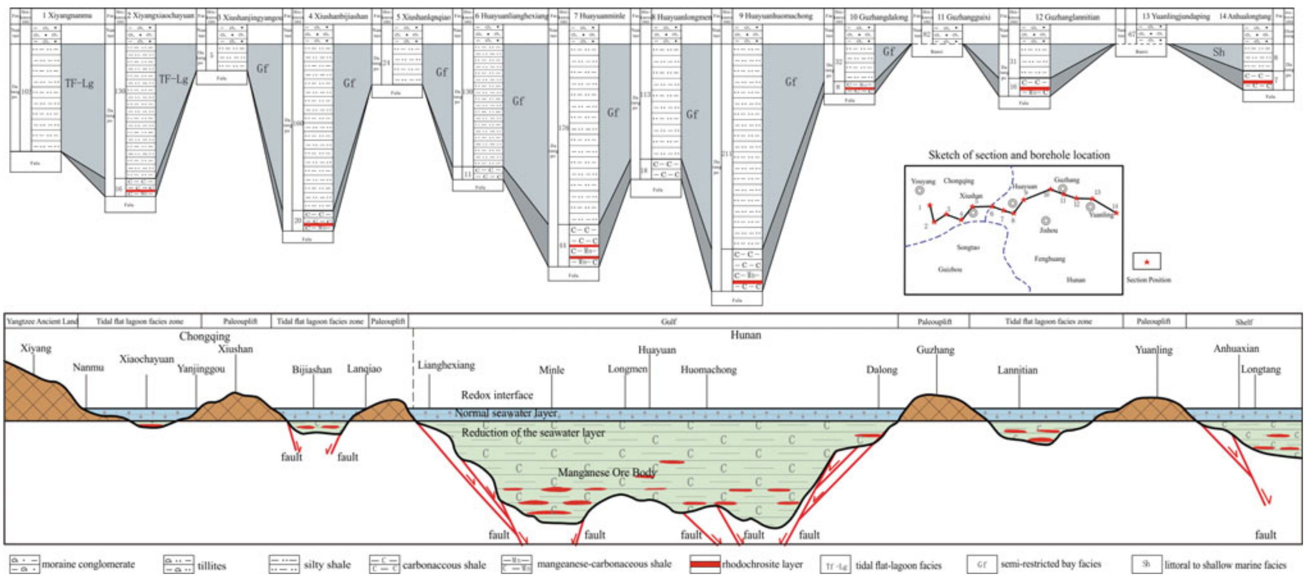

Fig. 3.2 Development model of black rock series of Datangpo formation of Nanhua system in Sichuan Basin and its periphery (modified according to Zou et al. 2020)

different in different facies belts, that is, the formation of sedimentary relatively organic-rich shale has an internal control role (Zheng et al. 2013; Mou et al. 2016).

Firstly, the sedimentary environment controls source rocks' thickness, distribution area and distribution law. It is of great significance to study the formation environment of source rocks and their control over shale gas development (Ma et al. 2014). For the geological survey, exploration and development of shale gas, source rocks is the basic material basis. Today's research and exploration practice show that the main basis for the generation and occurrence of shale gas is the thickness of source rock, and the hydrocarbon generation potential of source rock formed in shallow sea shelf (including deep-water shelf area), slope, semi-deep sea and other environments is greater. If the thickness of the source rock is greater than 30 m, the gas remaining in shale is more conducive to enrichment and accumulation due to the influence of its own sealing layer; its shale gas development conditions are better (Li et al. 2008; Xu et al. 2011; Wang et al. 2013). At the same time, the main distribution law of shale gas is also directly reflected in the distribution area and fine temporal and spatial distribution of this set of source rocks. This objectively reflects the main (fundamental) factor position of sedimentation and sedimentary environment on shale gas development, which controls the thickness, distribution area and temporal and spatial distribution law of high-quality source rocks (Wang et al. 2015; Mou et al. 2016). The preliminary study of shale gas potential strata such as the Niutitang Formation and Longmaxi Formation in the whole South China shows that they are developed in a favorable deep-water sedimentary environment similar to the shale gas development strata in North America, and the "congenital conditions" are better; further sedimentary facies, microfacies and even fine lithofacies types, such as (calcium-containing) carbonaceous (siliceous) mudstone and silty (calcium-containing) carbonaceous mudstone in deep-water shelf environment, have better shale gas development conditions. In addition, factors such as underwater hypoxia retention sub-environment and slow deposition rate basically control the development and distribution of high-quality source rocks of Niutitang Formation and Longmaxi Formation in this area, so that the source rocks in whole area have the characteristics of large thickness and wide distribution area and are the main target strata for shale gas geological survey and further exploration and development (Zhang et al. 2012; Zhang 2015).

The actual exploration and development of the Longmaxi Formation shale gas reservoir in Jiaoshiba area further show that the source rocks section realizing industrial gas flow is mainly concentrated in the lower part of its black rock series (Guo 2016), which puts forward higher requirements for the identification of fine sedimentary sequences of source rocks. However, it is well known that the sedimentary environment plays a decisive role in controlling the transgression and regression sequences of source rocks during the sedimentary period and then affects the development of their sedimentary sequences. Therefore, it further reflects the control of sedimentary facies and sedimentary environment on shale gas development. In addition, some studies show that some specific sedimentary environments also affect the transformation and development of source rocks after deposition. For example, statistical analysis shows that the favorable sedimentary environment makes the favorable lithofacies types formed in the early stage of the reservoir space of source rocks which are not easy to be transformed by later diagenesis.

To sum up, as the carrier of shale gas, the source rock itself has a very close relationship with the sedimentary environment. The latter controls the formation of source rocks and the geometric shape and spatial distribution of source rocks. Through the final paleogeographic analysis, it is helpful to recognize the shape of source rocks and predict the fine spatial distribution law of source rocks, especially the fine spatial distribution law of shale gas favorable intervals in Jiaoshiba area.

Secondly, the enrichment of organic matter is the main controlling factor and basic element conducive to the development of shale gas (reservoir). It affected the amount of hydrocarbon generation and controlled the adsorption capacity of shale gas. It is not only the key evaluation factor of shale gas reservoir formation, but also the main research object of shale gas geological survey and exploration and development (Fu et al. 2008; Li et al. 2008). Studies have shown that the types and distribution of sediments of high-quality source rocks, such as the types and abundance of hydrocarbon-generating parent materials and kerogen type of source rocks, were not only controlled by sedimentary facies and sedimentary environment, but also provided favorable conditions for biological activities, reproduction and prosperity of hydrocarbon-generating parent materials, including high original productivity, limited retention anoxic reduction environment, appropriate deposition rate, rising ocean current submarine hydrothermal activity, ice age, etc. It is concluded that the sedimentary facies (environment) determine the conditions for the enrichment (degree) and preservation of organic matter in organic-rich shale, so as to control the organic matter content and type of organic-rich shale as a whole.

During the deposition period of the organic-rich shale development section of the Early Silurian Longmaxi Formation in Southern China, the paleoclimate warmed rapidly, resulting in the rapid melting of the Late Ordovician Hirnantian glaciers and the rapid rise of sea level in the initial stage. Combined with the tectonic pattern at that time, the area rapidly evolved into an occluded “bay-type” sedimentary environment (Li et al. 2008; Zhang et al. 2012; Mou et al. 2010, 2014; Ge et al. 2013a, b, 2014). Under the rapid transgressive environment, not only the intake of terrigenous clastic materials unfavorable to the development of organic-rich shale is greatly reduced (Hickey and Henk 2007), but also the formation of the layered sedimentary water body is exacerbated. Firstly, the rapid warming of paleoclimate makes the surface water of sedimentary water rich in oxygen due to direct solar radiation, the bottom water cannot get solar radiation due to rapid transgression, and it continues to maintain the ancient water temperature during the ice age for a long time, so it lacks oxygen. The former is suitable for the growth, life and reproduction of a large number of organisms. Together with the abundant planktonic fossils dominated by graptolites in the bottom water body, it creates high productivity conditions, provides rich sources of organic matter for sediments and is conducive to the enrichment of organic matter; in the latter, anoxic reduction conditions hinder the decomposition of organic matter and are conducive to the preservation of organic matter (Clavert 1987; Chen et al. 1987, 2000; Curtis 2002; Chen et al. 2011; Chen et al. 2006; Li et al. 2008; Fu et al. 2011; Cheng et al. 2013; Wang 2015; Mou et al. 2016). At the same time, due to the deep-water shelf environment and the low temperature of the bottom water body near the center of the basin, the carbonate minerals in the water body are difficult to be saturated for chemical precipitation, while the settlement of silicon-rich organisms in the upper water body promotes the formation of siliceous shale, which is conducive to the hydraulic fracturing of shale gas. In addition, geological practice and simulation experiments show that when the deposition rate is slow, it is not conducive to the preservation of organic matter; when the deposition rate is fast, the content of organic matter per unit volume weight is significantly diluted and reduced. Therefore, an appropriate deposition rate is also a favorable condition for the deposition of source rocks and the enrichment of organic matter (Chen et al. 2006; Zhang et al. 2013; Wang et al. 2015; Mou et al. 2016). Due to the lowest loss of rock porosity, it is conducive to the formation of good shale gas reservoirs (He et al. 2010). Feng et al. (2008) believe that the early deposition thickness of Longmaxi Formation in Southern China is 20–200 m. Its deposition rate is about 6–60 m/Ma, which is very conducive to the development of source rocks and the enrichment and preservation of organic matter, which is closely related to the favorable sedimentary environment in the early stage of Longmaxi Formation and the conditions such as hypoxia and high biological productivity in this environment. In sharp contrast, the late deposition of Longmaxi Formation, although the overall sedimentary environment is still in a relatively stagnant environment, is already a relatively shallow sedimentary environment (Zhang et al. 2012). In this environment, it not only has a rapid deposition rate, but the large addition of terrigenous clastic sediments increases the dilution of organic matter, reduces the abundance of organic matter in source rocks and is not conducive to the development and accumulation of shale gas.

Hill et al. (2007) also found through the detailed study of Barnett shale that under the deep-water sedimentary environment, the biomarkers of this set of shale show favorable conditions such as hypoxia, normal salinity and strong upwelling. Under this specific sedimentary environment (deep water), in addition to the anoxic conditions similar to the sedimentary period of organic-rich shale in the Early Longmaxi Formation in Southern China, the biological activities in the sedimentary environment of Barnett shale are also very active due to the active upwelling current. Barnett shale is often symbiotic with phosphorus-rich minerals, which ultimately determines that this set of source rocks has high organic matter content, good organic matter type and good enrichment degree.

In fact, the enrichment and preservation process of organic matter in Barnett organic-rich shale in the USA and the early organic-rich shale in Longmaxi Formation in Southern China, as well as the types and abundances determined by this process, is closely related to favorable factors such as biological original productivity, ancient water depth, ancient climate, limited retention hypoxia, rising ocean current and appropriate deposition rate, which affect the development of hydrocarbon-generating parent materials of source rocks; when these factors reach the optimal configuration, it is conducive to the development of higher-quality source rocks and the enrichment and preservation of organic matter. These factors are restricted by the sedimentary environment, which controls the development of relevant conditions. They are the relevant parameters of sedimentary facies. In a specific period and sedimentary environment, one or two factors can affect or change other factors, which has become the most critical factor affecting the development of high-quality source rocks and the enrichment and preservation of organic matter. Therefore, the sedimentary environment plays a very important role in the development of source rocks with high organic matter abundance (Fu et al. 2008; Li et al. 2008; Liang et al. 2011; Wang et al. 2015; Zhang et al. 2015). Sedimentary facies are the basis and main controlling factor for the development of source rocks and then control the type and abundance of organic matter in source rocks.

Moreover, as the key factor of shale gas content (i.e., resource evaluation and favorable block optimization) (Yang et al. 2012), the thickness, distribution area, organic carbon content and types of organic shale are not only controlled by the sedimentary environment, but also as the key factor of shale gas “dessert” area, whether shale gas can be economically developed and how the output is; reservoir characteristics such as rock types, mineral composition, brittleness, porosity (including fractures) and permeability of source rocks are also controlled by sedimentary environment (Kinley et al. 2008; Loucks et al. 2009; Yang et al. 2012; Wang et al. 2014, 2015; Guo et al. 2015; Mou et al. 2016).

The sedimentary environment controls the development of source rocks, and it affects the microlithofacies types and mineral components of source rocks. There are many types of lithofacies of source rock, the carrier of shale gas, including siliceous shale, calcareous shale, (calcium-containing) carbonaceous (siliceous) mudstone, silty sand (calcium-containing) carbonaceous mudstone, carbonaceous (calcium-containing) silty mudstone, carbonaceous mudstone and carbonaceous argillaceous limestone, which are formed in different sedimentary environments or in different sub-environments or microenvironments of the same environment, sedimentary system, paleowater depth; many environmental factors such as paleoclimate directly affect their development characteristics and determine their vertical and horizontal changes and migration; it is the development of lithofacies types, and mineral components of source rocks in different sedimentary facies belts, sedimentary surfaces belts and microfacies belts are different. This difference and related environmental conditions not only determined the development of reservoir physical properties such as porosity and pore structure of source rocks itself, but also directly affected the enrichment and accumulation of shale gas as an internal controlled factors, but also affected the development and formation of fractures in source rocks and then affected the later development effect of shale gas as an external controlled factor, which were also the key factors affecting the brittle content of shale (Curtis 2002; Jarvie et al. 2007; Wang et al. 2012a, b, c, d; Wang et al. 2013, 2014, 2015; Mou et al. 2016).

The sedimentary environment determines the characteristics of rock facies types and mineral components of source rocks. Lithofacies types and mineral components are also correlated with organic matter abundance. Wang et al. (2014, 2015) analyzed the fine lithofacies types of source rocks in the shale gas development interval of Longmaxi Formation in Southern Sichuan and its periphery and found that the (calcium-containing) carbonaceous (siliceous) mudstone and silty (calcium-containing) carbonaceous mudstone developed in the deep-water shelf environment have high organic carbon content, and most of them were developed in the early stage of transgression. If the sedimentary water body was deep, the carbonate mineral content was low and the siliceous content was high; most of them were siliceous shale, which was conducive to the enrichment and accumulation of shale gas and the later exploration and development. Carbonaceous (calcium-containing) silty mudstone, carbonaceous mudstone and carbonaceous argillaceous limestone were mainly developed in shallow shelf environments. Although their organic carbon content was also relatively high, the organic carbon content gradually decreases with the increase of the content of clastic particles and carbonate minerals. The correlation between the former and organic carbon content was more sensitive, indicating that terrigenous clasts provide a large amount of oxygen-rich sedimentary environment, which was not conducive to the preservation of organic matter. The increase of carbonate minerals may only dilute the abundance of organic matter, which was consistent with the previous view. The flat tidal environment with shallow water body, high oxygen content and rapid warming is mainly a set of silty mudstone and argillaceous siltstone, which are not conducive to the preservation of organic matter, and the content of terrigenous debris and carbonate minerals was very high, so it is difficult to form a high abundance of organic carbon. Wu et al. (2016) divided and studied the shale facies of the Wufeng Formation-Longmaxi Formation in the Fuling gas field and founded that there were mainly eight kinds of lithofacies: siliceous shale facies, mixed siliceous shale facies, clay-containing siliceous shale facies, ash/silicon-containing mixed shale facies, clay/silicon-containing mixed shale facies, mixed shale facies, silicon-containing clayey shale facies and clay/ash-containing mixed shale facies. Different types of lithofacies indicate different sedimentary environments. It is determined that the mixed siliceous shale facies and clay-containing siliceous shale facies in the study area are class I dominant facies, and the clay/silica-containing mixed shale facies are class II dominant facies. The above research results comprehensively reflected that not only the development of organic matter in source rocks was controlled by the sedimentary environment, but also the uncompensated and anoxic deep-water environment with low carbonate mineral content was also conducive to the preservation of organic matter (Zhang et al. 2012; Cheng et al. 2013), but also the development characteristics of fine lithofacies types and mineral components of source rocks are also controlled by the sedimentary environment. It is precisely because the related sedimentation in this environment jointly controls the organic matter, lithofacies types and mineral components of source rocks, resulting in the correlation between lithofacies types, mineral components and organic matter abundance.

From the control factors of the development characteristics of source rocks reservoir, the organic carbon content, mineral composition and organic matter maturity of source rocks are the three most important factors for the development of source rocks reservoir (Curtis 2002; Jarvie et al. 2005, 2007). It is obvious that these three important factors are controlled by the sedimentary environment. The higher the TOC content, the appropriate mineral component content and the gas content of the source rocks, the easier it is to form a favorable source rocks reservoir and the more conducive it is to the development and accumulation of shale gas. To a certain extent, it can be directly summarized that the sedimentary environment controls the development and distribution of the source rocks and reservoir (Bowker 2007). For example, Guo et al. (2015) took the source rocks of the Shanxi Formation in the north of Ordos Basin as the research object. They studied the control of different sedimentary (micro) relative source rocks reservoirs of the Shanxi Formation. Firstly, seven types of lithofacies were identified through the study of sedimentary microfacies of source rocks of the Shanxi Formation. Further, through the study of the organic matter abundance, type characteristics and mineral composition characteristics of these lithofacies types, it was pointed out that the organic matter abundance of the four lithofacies types ((gray) black carbonaceous shale, (gray) black carbonaceous shale, (gray) black carbonaceous (silty) sandy shale and (dark) gray carbonaceous shale) controlled by the plant-rich swamp microfacies and the plant poor swamp microfacies was higher; the content of mineral components was more conducive to the development of shale gas; there is a better correlation between these microlithofacies types and their own mineral component content and organic matter abundance, and there is an obvious positive correlation between organic matter content (TOC) of favorable lithofacies types and adsorbed gas content. This is consistent with Bowker (2007). Considering the symbiosis of Shanxi Formation source rocks reservoir and coal seam and the symbiosis of plant-rich swamp microfacies and plant poor swamp microfacies with coal forming peat swamp microfacies and peat flat microfacies, it is a more favorable source rocks development environment and indirectly reflects the important influence and control of sedimentary environment on the development and distribution of source rock reservoir.

3.2.3 Lithofacies Paleogeography and Shale Gas

In the geological survey of shale gas, the study of regional sedimentary facies and sedimentary environment can not only clarify the basic geological characteristics of source rocks, but also understand the basic geological characteristics of shale gas development; on this basis, the temporal and spatial distribution of favorable facies zones of source rocks can be clarified through the mapping method and technology of lithofacies paleogeography; finally, on the distribution map of favorable sedimentary microfacies and lithofacies paleogeography of shale gas, further comprehensive research will be carried out to determine the prospective area, favorable area and target area of shale gas development, so as to provide a scientific basis for shale gas exploration.

From the perspective of the actual effect of China's shale gas geological survey and exploration and development, although the preliminary shale gas survey shows that the early Paleozoic marine source rocks strata in China, especially in Southern China, have great shale gas resource potential, through nearly a decade of research and geological survey, only the organic shale rich in Ordovician Wufeng Formation-Silurian Longmaxi Formation in some areas of Sichuan Basin has realized industrial development. It is reasonable to say that the study of these sets of source rocks strata in Southern China also has a certain history, and it should have a comprehensive and clear grasp of the basic geological conditions of oil and gas. However, the reality is that it not only has a shale gas reservoir, but its basic resource background also has not been clarified, there is still a long way to go, and there are still many studies to be strengthened. Moreover, even as a source rocks of conventional oil and gas reservoirs, its specific distribution law and other related research are still slightly insufficient.

First of all, there are a lack of comprehensive and profound understanding of shale gas research. The understanding of history refers to the understanding from the sedimentary pattern and characteristics of various geological ages; it is from the pattern and characteristics of paleogeography and paleostructure and the law of historical evolution. The overall understanding and research are to understand the comprehensive and systematic geological evolution law of "the ancient structure controls the development of sedimentary basins during the development period of source rocks, the types of sedimentary basins controls the sedimentary facies of source rocks, and the sedimentary environment determines the development of various geological factors of shale gas". Deep understanding refers to the fine understanding and research on the petrology, geochemistry and reservoir space of source rocks segments and the qualitative leap from qualitative to quantitative.

Secondly, taking the Sichuan Basin in Southern China as an example, in the process of sedimentary evolution of the basin, there has been a sedimentary environment which is very conducive to the formation of source rocks and the development of favorable factors for the formation of shale gas. However, the research and evaluation of shale gas in this area, as well as the optimization of prospective areas, favorable areas and target areas, still need to be further explored (Mou et al. 2011, 2012, 2016). Therefore, on the basis of reasonable theory, using appropriate working means to carry out the basic geological survey is the key to shale gas exploration in the Sichuan Basin with superior structural and sedimentary conditions. That is, we should start with the most fundamental geological situation research and start with the geological background of hydrocarbon source rocks development, that is, the basic paleogeographic research, and then follow the sequence of shale gas research, shale gas development conditions research and shale gas exploration and development without taking shortcuts.

Predecessors have carried out at least three rounds of systematic studies on sedimentary facies and lithofacies paleogeography with different scales and fine degrees in Sichuan Basin (Mou et al., 1992, 2010, 2011, 2016; Xu et al. 1993; Liu and Xu 1994; Ma and Chu 2008), preliminarily showing the Early Cambrian Qiognzhusi period (Niutitang Formation) during the deposition of high-quality source rocks in the Late Ordovician Wufeng period (the Wufeng Formation) and the Early Silurian long period (the Longmaxi Formation); these sets of source rocks are widely distributed and stably distributed regionally, which are potential shale gas development strata. The research shows that the basic geological research and determination of source rocks, especially the determination of high-quality source rocks, can play a very important role and significance in scientifically evaluating the oil and gas resource potential of the basin and deeply revealing the laws of oil and gas generation, migration, accumulation and enrichment (Lu et al. 2006; Hou et al. 2008). Among them, for the shale gas reservoir integrating source and reservoir, the fine research on its material basis and control factors is particularly important. Therefore, systematic fine sedimentary microfacies and large-scale lithofacies paleogeography research should be carried out with the source rocks development area as the center of focus and the paleogeographic sedimentary environment for shale gas development as the center or premise, so as to determine the source rock characteristics and spatial distribution of shale gas development intervals, and take lithofacies paleogeography mapping technology as the key method and technology, based on the favorable microfacies belt or sedimentary environment for shale gas development. Conduct research on shale gas evaluation parameters such as source rocks thickness, organic matter content and mineral composition, and finally select appropriate parameters for superposition research, so as to find and delineate the distribution locations and zones with good coupling, such as the favorable sedimentary microfacies belt of source rocks, high organic matter content and appropriate mineral composition content of source rocks and take them as the preferred target and preferred area for shale gas exploration and development (Mou et al. 2016).

In fact, the research and practice of China's energy resources show that the research and mapping technology related to lithofacies paleogeography can actively and effectively serve the prediction and exploration of various minerals (Feng et al. 1997, 1999, 2005; Mou et al. 2010, 2011, 2106). Nowadays, the scope of prospecting work guided by lithofacies paleogeography research and related mapping technology has been extended to almost all mineral resources, especially in the field of oil and gas. It has a more prominent effect in guiding oil and gas geological survey, prediction, exploration and development. It not only serves as basic geological science research for the geological survey of oil and gas resources. Moreover, it is often used as a key method and technical means to serve the prediction and exploration of oil and gas resources (Mou et al. 2016). It should be said that this is one of the main characteristics of lithofacies paleogeography in China, and it is also an important reason for the prosperity of lithofacies paleogeography.

Of course, the oil and gas resources mentioned above often refer to conventional oil and gas resources. As for the development of shale gas reservoirs, our views and suggestions are still the research of lithofacies paleogeography and its related mapping methods and technologies, when we choose what theories and related methods and technologies to serve the geological survey or prediction, exploration and development of shale gas, can accurately and well complete the relevant tasks (Mou et al. 2016). Based on the study of regional sedimentary facies and the mapping method of lithofacies paleogeography, the temporal and spatial distribution of favorable facies zones of source rocks can be clarified, so as to provide the basis and direction for shale gas exploration. Therefore, taking lithofacies paleogeography research and mapping as the basic method and key technology can also provide guidance for the geological survey of shale gas (Mou et al. 2016).

In short, sedimentary facies control the basic geological conditions of shale gas development and its related properties and spatial distribution (such as the thickness, distribution area, organic matter content and type, mineral composition) for the geological survey of shale gas under stable structural units, and the detailed and systematic study of sedimentary facies and lithofacies paleogeography is an important basis and premise for the optimization of favorable areas for shale gas. It is also theoretical guidance and key methods and technologies (Mou et al. 2016). To carry out the geological survey of shale gas, we must first carry out comprehensive, overall and fine research and mapping on the paleogeographic environment of source rocks, especially high-quality source rocks. Then, on this basis, focusing on the sedimentary microfacies belt or sedimentary environment conducive to the development of shale gas, comprehensively study the conditions or parameters of shale gas development or evaluation, select appropriate shale gas influence parameters and carry out the coupling superposition of relevant contour maps on the fine lithofacies paleogeographic map, so as to carry out the optimization of shale gas scenic spots, favorable areas and target areas. After such a systematic step, it is possible to grasp the key and key of shale gas geological investigation and research, so as to provide a more scientific basis for the final exploration and development of shale gas and realize the breakthrough of shale gas.

As mentioned above, Xie (1947) put forward the forward-looking view of paleogeography as a guide for prospecting as early as several decades ago. The research and mapping of sedimentary facies, lithofacies and paleogeography have also been widely proved to play a basic and key guiding role in the success of oil and gas exploration industry. As Mou et al. (2011, 2012) said, when conducting a geological survey of oil and gas resources and further exploration and development in an area, the different disciplines will put forward corresponding suggestions and understanding from different angles. However, sedimentary geology, as one of the most basic disciplines, should be the basis and necessary content of research and work, but also a method. Its core is sedimentology and lithofacies paleogeography. The geological survey of shale gas is no exception. For the basic geological survey of shale gas in China, which is already in the stage of extensive development, the research and mapping of sedimentary facies and lithofacies paleogeography are indispensable. It can be used as the key basic geological theory and method to provide guidance for the geological survey of shale gas, which is the first step of the basic work.

Theoretically, because the information of lithofacies paleogeography reconstruction comes from geological records, any information on the sedimentary environment in the sedimentary period of source rocks will be directly or indirectly branded and preserved in the geological stratigraphic records. However, due to the limited technical means and cognitive level of human beings, as well as the destruction and change of geological records, some congenital deficiencies or even sedimentary discontinuities are caused by later structural reasons. It brings great difficulties for researchers to obtain, interpret and retrieve these paleo-environmental information, resulting in great asymmetry in quantity, authenticity and reliability between the extremely rich and complex information in geological records and the parts available to researchers at present (Wang et al. 2003), which hinders the reconstruction research of lithofacies paleogeography and the geological investigation of shale gas resources to a certain extent. Therefore, on the basis of paying attention to the research and mapping of sedimentology and lithofacies paleogeography, we should also pay attention to the research of other disciplines or theoretical technology, such as structural geology and the selection of geochemical analysis and testing methods, so as to more effectively carry out and complete the task and goal of shale gas geological survey. However, the understanding of shale gas geological survey with sedimentology and paleogeography as the core theory and key technical methods cannot be deviated. Extensive and comprehensive lithofacies paleogeography can be used as a guide for shale gas geological survey, and relevant lithofacies paleogeography mapping technology can be used as a key technical method to realize the task of shale gas geological survey, so as to provide a solid foundation and scientific basis for further exploration and development of shale gas reservoir (Mou et al. 2016). The means of other disciplines (such as geochemistry) can only be an auxiliary means. The main purpose is to evaluate the geological conditions of shale gas development and then provide a reference basis for the optimization of shale gas favorable areas based on the study of lithofacies paleogeography and mapping. This consensus and methodological understanding should be the product of the high combination of paleogeography and shale gas exploration and development practice (Mou et al. 2016). It should be emphasized that in the process of shale gas geological survey, sedimentology and lithofacies paleogeography are not only a regional, multi-information and multi-disciplinary comprehensive basic research, but also more importantly, they are a method of shale gas geological survey and a method of "looking for" shale gas.

3.2.4 Specific Methods and Steps

1. Restoration of prototype sedimentary basin

Organic-rich shale can be developed in rift basins (also divided into the intercontinental rift and intracontinental rift), passive continental margin basins, ocean basins, Craton Basins, trench-arc basin, system basins (such as intra-arc basins), residual basins, back-arc Foreland Basins, peripheral Foreland Basins and other qualitative basins. They represent the types of sedimentary basins under different plate tectonic backgrounds and dynamic mechanisms. It reflects the different evolution geological history from the Cratonic Basins extension stage, decline stage, residual stage and suture orogeny stage. However, most of today's sedimentary basins have been transformed by different tectonic activities in the later stage and show the type of superimposed sedimentary basin. Importantly, theory and practice have proved that a complete shale basin is very important for the development of shale gas. At the same time, those complete favorable structural units not only have high-quality source rocks required for shale gas development, but also have good caprock and other conditions which will be the key objects and areas for specific shale gas geological survey in the next step. It affects the specific deployment of shale gas geological survey.

Therefore, the first step of a shale gas geological survey is to restore the original properties of places rich in organic shale.

Firstly, with the idea of "tectonic controlled the development of basins ", it is not only necessary to study the plate tectonic background and the dynamic mechanism of the sedimentary basin during the development of organic shale in combination with the analysis of the relevant tectonic background. Secondly, we should study the evolutionary history of the sedimentary basin in this period, judge its evolution stage and trace the original nature of the sedimentary basin in this period from the perspective of geological history. Finally, on the basis of previous research results and practical basis, comprehensively and objectively identify and restore the types of sedimentary basins in the development period of organic-rich shale, judge their complete types of sedimentary basins and further screen or optimize the types of sedimentary basins that are more conducive to the development of high-quality source rocks for shale gas accumulation, such as the Craton Basin and the Foreland Basins. So as to restore their scope, the size, shape and scale lay the foundation for the following specific shale gas geological survey and provide a measurement reference and scientific basis.

2. Lithofacies paleogeography research and mapping

(1) Research on point

The research on point includes the sedimentary facies, sedimentary microfacies, rock types and characteristics, geochemical characteristics, mineral composition characteristics and vertical variation law of source rocks, in order to clarify the relevant basic geological characteristics of source rocks.

The specific approach is, through a large number of detailed field work, first to carry out the research on the fine lithology characteristics of source rocks from specific points, establish the backbone section or even "iron pillar" of the petrological characteristics of source rocks and then carry out the fine research on the types and characteristics of sedimentary microfacies (rock). If conditions permit, the observation and research of cores can also be strengthened. On this basis, through a certain degree of fine sampling, TOC, Ro and other parameters of source rocks reflecting shale gas development conditions are analyzed, various indoor identification, analysis, laboratory test and comprehensive research work are carried out, the variation law on the profile is summarized, and different gas-bearing source rock segments on a single point are divided. Through geochemical analysis, the types and contents of conventional minerals and clay minerals in different gas-bearing source rocks sections are analyzed, and their variation laws in profile and plane are summarized. Combined with the field and indoor comprehensive research results, the formation environment of different gas-bearing source rocks segments is further determined. Finally, establish a comprehensive histogram of the development characteristics of source rocks on the point, comprehensively clarify the various characteristics of the development of different gas-bearing source rocks segments from the point and complete the first goal of the shale gas geological survey.

(2) Research from point to surface

The research from point to surface is mainly to conduct vertical sedimentary sequence and horizontal comparison, clarify the spatial distribution law of source rocks and the vertical and horizontal changes of shale gas development conditions and prepare single-factor maps of shale gas development conditions.

After comprehensively clarifying the development characteristics of different gas-bearing source rocks segments at each point, through the field profile connection and drilling well-connection profile, comprehensively analyze the thickness, TOC, Ro, mineral composition, occurrence and distribution of different gas-bearing source rocks segments from point to surface and then analyze their vertical and horizontal variation laws. If possible, it is also necessary to study the buried depth through seismic and detailed drilling data to further clarify the temporal and spatial distribution law of source rocks and their characteristic conditions, such as area, and prepare various single-factor maps of shale gas development conditions.

(3) Lithofacies paleogeography research and mapping

With the mapping idea of "tectonic controlled the development of basins and sedimentary basins controlled the development of sedimentary facies", on the basis of the above two studies, through the research and mapping technology of lithofacies paleogeography, it shows the variation law of the thickness and range of source rock development, the evolution law of favorable sedimentary (micro)facies, the variation trend of buried depth, etc. and then comprehensively compiles the favorable sedimentary (micro)facies map and lithofacies paleogeography map of shale gas development.

Through the research of the above steps, we can clarify the temporal and spatial distribution law of source rocks, that is, the second task of the shale gas geological survey.

3.3 Optimization of Prospective Area, Favorable Area and Target Area

(1) Optimization of prospective area

After completing the basic research content of point 2, the shale gas geological survey work area has the basic conditions for the optimization of shale gas scenic spots. Only according to the actual situation of different areas of shale gas geological survey work, different evaluation factors for shale gas development should be selected, such as rock and mineral data of gas-bearing shale or 1–3 parameters such as thickness and distribution range comprehensively determined according to TOC and Ro of source rock; on the basis of lithofacies paleogeographic map, the scope of shale gas prospect can be basically defined by stacking relevant parameters and their isoline map with superposition method.

(2) Optimization of favorable area

Firstly, on the basis of detailed basic geological research such as point, line and plane and lithofacies paleogeography mapping, further carry out the research on fine favorable sedimentary microfacies and even fine favorable lithofacies of shale gas development, select more favorable gas-bearing shale intervals and prepare more elaborate lithofacies paleogeography map. Secondly, different evaluation parameters affecting shale gas development are comprehensively studied and selected based on more detailed lithofacies paleogeographic map and the actual situation of different zoning of shale gas geological survey. Generally, TOC (which can be divided into different standards such as >1.0% and >2.0%) and Ro are the main geochemical indicators of source rocks, combined with the research results of the mineral composition of source rocks. In the favorable sedimentary microfacies belt where the source rocks are developed, the superposition method is further used to stack the relevant parameters and their isoline map to couple the favorable blocks where the source rocks are developed. Finally, combined with the data obtained from the previous study on the gas content of source rocks and the preliminary data of resource potential, the areas with better comprehensive conditions are further selected in the coupled favorable blocks for the development of favorable source rocks as the preferred areas for the development of shale gas.

(3) Optimization of target area

Similarly, based on the lithofacies paleogeographic map and step (2), within the scope of the selected favorable area, the research results and maps of the reservoir capacity of source rocks (including the map of reservoir space type, reservoir physical properties, reservoir fractures and their change law, reservoir porosity, permeability and other data and index change map), the research data and results in map of diagenesis, the buried depth and occurrence of source rocks and other maps can be further superimposed and improve the geochemical index parameters reflecting the development degree of shale gas (e.g., increase the data of TOC contour map to more than 3.0%). Finally, according to the specific situation of shale gas geological survey zoning, we can comprehensively optimize the hydrocarbon source rocks development which are suitable for commercial development, that is, the shale gas development target area, considering the preservation conditions such as structural faults and other factors that need to be considered in industrial exploration and development.

Through the step-by-step method in Figs. 3.3 and 3.4, the third task of the shale gas geological survey, such as the

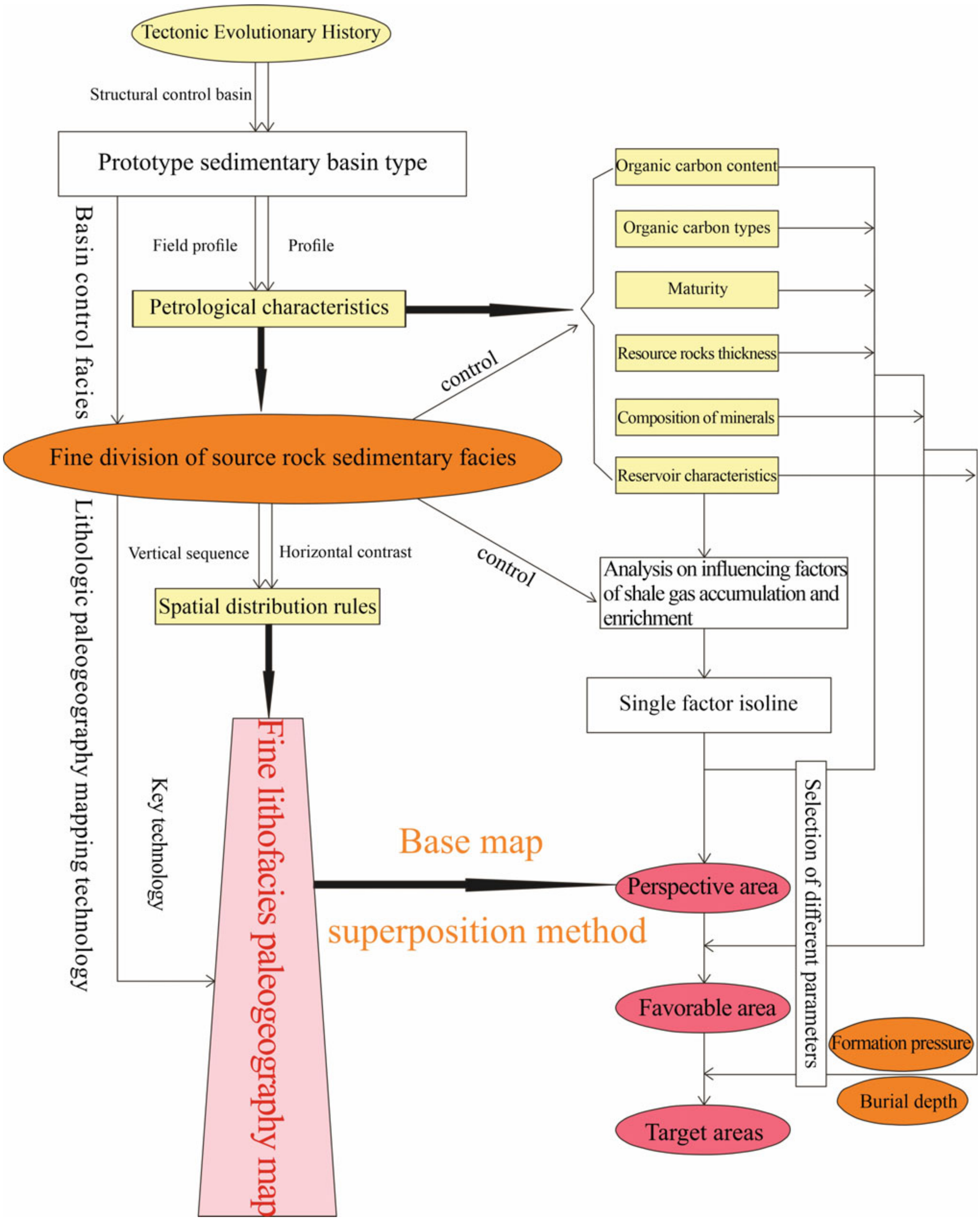

Fig. 3.3 Working methods (technical) steps of shale gas geological survey

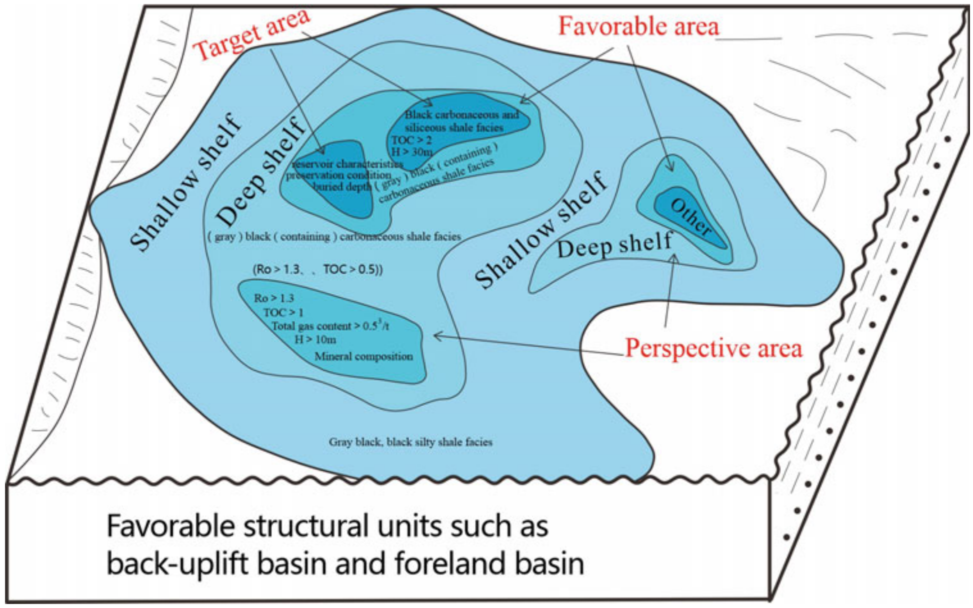

Fig. 3.4 Schematic diagram of the working method of shale gas geological survey

optimization of shale gas development prospect area, favorable area and target area, can be completed. In conclusion, the basic task of the shale gas geological survey can be better completed. In this process, the author emphasizes the theoretical basis and guiding role of lithofacies paleogeography research and the understanding of lithofacies paleogeography mapping technology as a key technical method.

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