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Sedimentation and lithofacies type of shale of Wufeng-Longmaxi Formation in western Chongqing area, China

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Abstract

The west Chongqing area is the key region of deep marine shale gas production on a continuous scale in Sichuan Basin, showing a good prospect of deep shale gas exploration and development. The shale source and storage resources of Upper Ordovician Wufeng Formation -Lower Silurian Longmaxi Formation are of good quality, and large areas of continuous and stable shale are developed in low energy and anaerobic environment of deep water shelf. The lithology of shale has a significant impact on its hydrocarbon generation ability, reservoir quality, and fracturing performance. Based on outcrop, X-ray diffraction, and geochemical data, this paper investigates the shale lithofacies and reservoir characteristics of the Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation. The research findings enhance our understanding of shale reservoir deposition and lithofacies in the study area while providing support for the efficient development of shale gas in the future. The results indicate that the study area is characterized by deep water shelf facies, primarily consisting of limestone facies, clay shale facies, calcareous shale facies, and calcareous-siliceous shale facies. Among these lithofacies types, clay-rich siliceous shale facies are most abundant followed by silica-rich/clay mixed shale facies. There are variations in vertical distribution between the south and north regions. In the south region, there is a transition from a clay-shale-facies association to a siliceous-shale-facies association before finally transitioning to a mixed-shale-facies association within the Wufeng-Longmaxi Formation. Conversely, in the north region, there is a trend of transitioning from a mixed-shale-facies association to a siliceous-shale-facies association before ultimately becoming a mixed-shale-facies association.

Keywords

Shale lithofacies; Wufeng Formation-Longmaxi Formation; lithofacies characteristic; rock type.

1. Introduction

With the increasingly prominent problem of energy demand in the world, shale gas has made major exploration breakthroughs in recent years, and has become one of the important oil and gas exploration and development fields[1-2]. Shale gas refers to the accumulation of natural gas mainly in adsorbed or free state in dark shale or high carbon mudstone, and a small part exists in dissolved state.At present, the shale gas of the Longmaxi Formation in the Sichuan Basin and the southeast margin area has been developed commercially on a scale at a depth of 3500m in shallow, middle-deep and middle-shallow layers. Fuling, Changning, Weiyuan, Zhaotong and other shale gas fields have been discovered, which has entered the golden era of rapid development of shale gas exploration and development, marking that China's shale gas has

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entered a new stage of large-scale industrial exploitation[3-4]. It is of great significance to the exploration and development of unconventional oil and gas in China and the optimization of energy structure. The West Chongqing area is located in the southeast of Sichuan Basin, at the junction of the low steep structural belt in south Sichuan and the gentle structural belt in middle Sichuan. Strata in the study area are Jurassic, Triassic, Permian, Silurian Longmaxi Formation, Ordovician Wufeng Formation and Baota Formation from top to bottom, while Carboniferous and Devonian are absent.

In this paper, the black shale of Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation is studied, and the marine shale lithofacies is finely divided and compared by using the three-terminal diagram of siliceous minerals-carbonate minerals-clay minerals, combined with the outcrop observation results, and the sedimentary characteristics and lithofacies types of deep shale of Wufeng Formation and Longmaxi Formation in western Chongqing are carefully studied in combination with the reservoir characteristics. In order to provide theoretical basis for well location optimization deployment and exploration and development in this area.

2. Geological Characteristics

2.1. Sedimentary Background

During the Late Ordovician Wufeng Period, rapid transgression occurred in the Sichuan Basin, and the whole east Sichuan area was in the deep water outer shelf environment, where a set of medium-thin layer gray-black, black siliceous mudstone and argillaceous siliceous shale deposits were mainly deposited. In Longmaxi stage of the early Silurian, the sea level began to decrease slowly on the basis of the rapid rise of the late Ordovician, and the Sichuan basin, especially the east Sichuan area, was in the shelf sedimentary area of relatively deep water. Due to the expansion of the surrounding ancient lands, such as the Leshan-Longnusi Ancient uplift in the central and western parts of the basin, the Central Guizhou Uplift in the south and the Kangdian ancient land in the southwest, the Sichuan Basin during this period was a semi-closed shelf environment with relatively deep water and was in a state of non-compensation. A set of sandy and argillaceous sediments were deposited in the shoreline-shallow shelf, while the other vast areas, especially the eastern Sichuan area, were in the relatively deep shelf environment and mainly accumulated a set of dark argillaceous and silty sediments rich in organic matter. According to the different sediments, it can be further divided into sedimentary microfacies such as sandy argillaceous deep water shelf and carbon argillaceous deep water shelf.

According to the regional geological background and specific sedimentary characteristics, such as lithology and special minerals, sedimentary structure, paleontology, geochemistry, well logging, etc., the method of restoring sedimentary environment by using phase markers, making full use of macro and micro observation, well logging and geochemical data, combined with the depth and depth of seawater, hydrodynamic conditions and natural geographical location, and referring to previous research results, It is generally believed that the Sichuan Basin was located in the coastal shelf environment during the Late Ordovician Wufeng-Early Silurian Longmaxi period, and the water body gradually deepened from west to east, while the eastern Sichuan Basin was mainly located in the shelf environment (facies) of the relatively deep water, and the slope environment (facies) could occur in some areas at some time.

2.2. Stratigraphic Characteristics

In the study area, the Devonian and Carboniferous sedimentary systems are missing, as well as extensive deposits from the Mesozoic and Cenozoic eras, similar to the overall situation in the Sichuan Basin. The uplift during the Early Caledonian period resulted in sedimentary gaps and

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discontinuities, with widespread absence of Devonian and Carboniferous systems. The central-upper Yangtze region is a shallow marine basin with limited continental shelf environment in the Pengshui area. During the Indosinian movement, the region transitioned to terrestrial deposition and experienced overall uplift and erosion. In the Yanshan movement period, the regional framework was mainly established with continuous thick clastic sedimentation. During the Himalayan movement period, there was intense uplift and erosion, resulting in rapid uplift during the Cretaceous and Neogene periods. The Longmaxi Formation and Wufeng Formation have well-developed shale layers. Triassic and Jurassic formations are exposed on surface while drilling reveals missing deposits from Devonian and Carboniferous systems but other formations are well developed. Among them, Wufeng-Longmaxi Formation is currently considered as one of most favorable target intervals for shale gas exploration due to its characteristics.

The early sedimentary characteristics of the Longmaxi Formation were similar to those of the Wufeng Formation, with the development of carbonaceous and siliceous black mud shale, which was blocked by the ancient structure in the early stage, resulting in limited and blocked reduced marine basin sedimentation. Due to the highly reduced deep water environment and abundant and high-quality hydrocarbon generating organic matter, the Longmaxi Formation has high oil and gas production potential, and the formation develops strip pyrite and various types of peltivists. The formation thickness is 400m~500m, and the distribution is stable.

3. Sedimentary facies and lithofacies characteristics

3.1. Sedimentary facies characteristics

3.1.1. Sedimentary facies symbol

The Longmaxi Formation is primarily composed of black and black-gray shales, exhibiting pyrite striations, bands, patches, and nodules. Fractures are not commonly observed; however, occasional occurrences of high-angle fractures and horizontal bedding fractures can be seen. Local graptolite development is present but generally at a low degree in terms of both crack formation and graptolite abundance.

The sedimentary structure is mainly horizontal bedding and massive bedding, local pyrite and sandy mass nodules, gravity flow sand body deposition, pyrite lamination and sandy banding development.

Paleontological features: The graptolites in local strata developed, most of the strata did not develop, mostly stellate or even almost did not develop. The developmental shell fossils of Guanyinqiao member of Wufeng Formation include brachiopods, trilobites and corals.

3.1.2. Sedimentary environment analysis

The paleosedimentary environment determines the original productivity and redox conditions to some extent, and the sedimentary geochemical elements record the evolution information and sedimentary characteristics of the paleosedimentary environment. Therefore, in order to distinguish the original productivity and redox conditions of organic rich black shale, the analysis of major and trace elements in shale has been widely used in the field of geology[5-7].

Paleosalinity: There are certain errors and limitations in determining the paleosalinity sedimentary environment with a single element ratio, so multiple element ratios are selected to determine the sedimentary environment characteristics. Mg is a typical sea-philic element, Al is a terrigenous element, Sr has stronger migration ability than Ba, and is more abundant in the distant sea area. In humid climate, with more precipitation, the salinity of water decreases gradually, and the content of Fe, Al, Ni, Ba and other elements in sedimentary rocks is higher. In dry climate, due to the evaporation of water, the salinity of water increases, Ca, Mg, Sr are precipitated to form a large number of salts deposited on the bottom. Sr/Ba value is a common

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index for the analysis of paleosalinity because the migration capacity of Ba and the solubility of sulfate compounds are much smaller than Sr, resulting in the combination of Ba and Sr with sulfate ions and precipitation under different salinity environments. Therefore, the paleosalinity characteristics of sedimentary water can be reflected by sediment Sr/Ba value. Previous studies have shown that Sr/Ba values less than 0.2, between 0.2 and 0.5 and greater than 0.5 indicate fresh water, brackish water and brackish water environment, respectively. The results of (Al+Fe) /(Ca+Mg) and Ca/(Ca+Fe) ratios show that the Wufeng-Longmaxi Formation in the study area was in a brackish water environment during the sedimentary period.

Paleoproductivity: Marine productivity is the foundation of Marine ecosystems and one of the main factors affecting the enrichment of organic matter. The geochemical index that can be used to indicate paleoproductivity is the P element. In addition, P/Al or P/Ti is usually used to remove the influence of terrigenous detritus, which can better represent the primary productivity of the paleo-ocean. Modern Marine studies have confirmed that the rate of Ba accumulation in seafloor sediments is positively correlated with biological productivity. Ba stays in seawater for a relatively long time, so it has a relatively high retention rate. However, Ba elements come from a wide range of sources, and only biological Ba is related to Marine productivity, so it is difficult to use Ba alone to judge the paleoproductivity during the sedimentary period. There is an obvious positive correlation between TOC and Mo content in organic-rich sediments, so Mo content can also be used as an index to measure the level of paleoproductivity. P element is not only one of the important nutrients necessary for the survival of organisms, but also participates in most of the processes of biological metabolic activities. At the same time, the bones of most Marine organisms are composed of phosphorus, which can be settled into the sediment with the remains of organisms after extinction. It can be seen that the level of ancient productivity increased greatly in the late Wufeng Formation and early Longmaxi Formation, and then fell back to the normal level.

REDOX environment: The composition and enrichment of trace elements in different redox environments are different, so the redox state of the sedimentary environment can be reconstructed by analyzing the ratio of trace elements in sediments or sedimentary rocks. Previous studies have found that trace elements such as V, Ni, Co, U and Th can better indicate the oxidation-reduction state of sedimentary environment. The values of V/ (V+Ni), U/Th, V/Cr and Ni/Co are used to analyze the oxidation-reduction conditions of the sedimentary environment of Longmaxi Formation. According to the analysis of various indexes, the whole sedimentary period of Wufeng-Longmaxi Formation in the study area was in a reducing environment, and the local horizon was in an anoxic and oxygen-poor environment.

3.2. Types and characteristics of shale lithofacies

3.2.1. Lithofacies Types

The sediments of Wufeng Formation-Longmaxi Formation in the west part of Chongqing are mainly dark mud-class clastic materials. At present, there are many lithofacies division schemes for shale, and the main lithofacies division schemes can be divided into three categories: based on mineral composition, based on mineral composition + TOC content, based on mineral composition + TOC content + sedimentary structure. No matter which division scheme is carried out, it is centered on mineral composition, which can not only reflect the sedimentary environment at that time, but also control the brittleness of rock and affect the fracturing effect[8-9]. In this paper, based on the naming scheme of "TOC + mineral composition", the mineral lithofacies are divided into 4 phases and 13 sub-lithofacies. That is, based on TOC value, the mineral lithofacies are divided into: carbon-rich (TOC > 4), high carbon (TOC 3-4), medium carbon (TOC 2-3), and low carbon (TOC < 2). According to the mineral component content, the shale is divided into: siliceous shale phase, calcium-rich siliceous shale phase, clay-rich siliceous

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shale phase, calcium-rich silica mixed shale phase, calcium-rich silica mixed shale phase, mixed shale phase, calcium-rich silica mixed shale phase, mudstone phase, silicon-rich clay shale phase, calcium-rich clay shale phase, limestone phase (carbonate mineral content is greater than 90%), silicon-rich calcareous shale phase, clay-rich calcareous shale phase.

3.2.2. Distribution Characteristics

According to the selected naming scheme, the classified rocks are named, and the clay-rich siliceous shale facies is the most abundant type of lithofacies, followed by silica-rich/clay mixed shale facies. The vertical evolution of shale facies in the first member of Wufeng Formation and Longmaxi Formation has the characteristics of tripartite. From the Wufeng Formation to Longmaxi Formation, the volume fraction of carbonate minerals gradually decreases. The silicite integral number is the highest in the middle of the first member of Longmaxi Formation. The integral number of clay ore objects is the highest in the upper part of the first member of Longmaxi Formation.

There are some differences in the vertical distribution of lithofacies between the southern and northern areas of the study area. The southern shale lithofacies shows a transition trend from the clay shale facies association to the siliceous shale facies association and then to the mixed shale facies association from bottom to top, which reflects the sedimentary environment changes of the Wufeng Formation and Longmaxi Formation in the study area to a certain extent. Among them, the Wufeng Formation is dominated by sily-containing clay shale facies due to the large input of terrigenous debris. During the sedimentary period of the first layer of Longmaxi Formation, the sea level rose, the terrigenous debris transport decreased, and the silica content increased, and the mixed siliceous shale facies dominated. There are two types of ash-bearing siliceous shale phase and mixed siliceous shale phase in the two layers of Longmaxi Formation. The shale lithofacies in the north shows a transition trend from the mixed shale facies association to the siliceous shale facies association and then to the mixed shale facies association. Among them, only mixed shale facies are developed in the first layer of Wufeng Formation and Longmaxi Formation.

The sedimentary evolution and distribution characteristics of shale lithofacies are mainly controlled by paleoprovenance, paleo-water depth, paleo-climate, paleo-salinity, and paleo-redox conditions. Different sedimentary conditions will produce different shale lithofacies evolution and combination modes. The transverse distribution of lithofacies in the Wufeng-Longmaxi Formation in the study area has strong heterogeneity and poor continuity. Laterally, the sedimentary thickness of the Longmaxi Formation is relatively stable, while that of the Wufeng Formation changes greatly, showing the characteristics of first thinning and then thickening from southwest to northeast. During the sedimentary period of Wufeng Formation, the clay content increased continuously from southwest to northeast, which resulted in the transition from mixed shale to mixed clay shale phase.

4. Conclusion

(1)The Wufeng-Longmaxi Formation in the study area was in deep water shelf environment in the early sedimentary stage. The exposed strata are Triassic - Jurassic, anticlinal Triassic and synclinal Jurassic.

(2)Based on the "TOC+ mineral composition" naming scheme, the names of mineral lithofacies are divided into 4 facies and 13 sublithofacies.

(3)The lithofacies in the southern part of west Chongqing area show a transition trend from the clay shale facies association to the siliceous shale facies association and then to the mixed shale facies association; The northern lithofacies shows a transition trend from the mixed shale facies association to the siliceous shale facies association and then to the mixed shale facies association from bottom to top.

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