



Original research paper

Accumulation condition and favorable area evaluation of shale gas from the Niutitang Formation in northern Guizhou, South China

Xianqing Li^{a,b,*}, Jizhen Zhang^{a,b}, Yuan Wang^{a,b}, Man Guo^{a,b}, Zhe Wang^{a,b}, Feiyu Wang^{c,d}

^a State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), Beijing, 100083, China

^b College of Geosciences and Surveying Engineering, China University of Mining and Technology (Beijing), Beijing, 100083, China

^c State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum (Beijing), Beijing, 102249, China

^d College of Geosciences, China University of Petroleum (Beijing), Beijing, 102249, China

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Abstract

In order to investigate the potential of the Lower Cambrian shale gas in South China, a study on the accumulation condition of shale gas from the Niutitang Formation was conducted. In addition, the favorable accumulation area of shale gas in northern Guizhou was evaluated. The study and evaluation were both analyzed according to the geochemical analysis data of the core and outcrop samples in this paper. The result shows that the Niutitang Formation shale in northern Guizhou is formed in the shallow sea sedimentary environment, which features moderate buried depth (<3000 m), high organic-rich shale thickness (30–110 m), high organic abundance (average $TOC > 3.0\%$), type I kerogens, over-mature thermal evolution level ($R_o > 2.0\%$), low porosity, abundant micro- and nano-meter pores and fractures, rich brittle mineral (average content >40%), and relatively high gas content (average $1.5 \text{ m}^3/\text{t}$). The aforementioned feature indicates that the Niutitang Formation in northern Guizhou has good accumulation condition for shale gas. Through the studies above, it is proposed that the southeastern Shiqian Yuqing Shibing area is the most favorable area for shale gas accumulation in northern Guizhou.

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Keywords: Shale gas; Accumulation condition; Favorable area evaluation; Niutitang Formation; Organic-rich shale; Northern guizhou

1. Introduction

The increasing demand for energy as well as the continuous depletion of conventional oil and gas resources have resulted in unconventional energy resources such as shale gas resources, which have attracted widespread attention in the recent years [1–3]. The tremendously successful exploration and development of marine shale gas in North American has triggered a worldwide upsurge. Thus, the area has become a new bright

spot in the field of global natural gas exploration and development [4–11]. Recent shale gas exploration that has been carried out attains significant progress in many countries such as England, Germany, India and Australia, especially in China. However, the same cannot be said for except the United States and Canada [1–15]. Shale gas, as a significant kind of unconventional natural gas, is generated from the organic-rich shale reservoirs developed with ultra-low porosity and permeability [1,4]. The primary composition of shale gas is methane, and it is usually stored in the pore-fracture system as free gas or adsorbed gas on the surface of organic matter and clay minerals [7–11]. Shale, as a self-contained that has a self-reservoir system, shows excellent potential for hydrocarbon generation [1,4,7–11]. In 2013, the U.S. Energy Information Administration (EIA) initially proposed that the quantities of shale gas

* Corresponding author. State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), Beijing, 100083, China.

E-mail address: lixq@cumtb.edu.cn (X. Li).

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resources can reach approximately 7299 trillion cubic feet all over the world. Furthermore, the technically recoverable shale gas resources can reach $36.1 \times 10^{12} \text{ m}^3$ in China, indicating a tremendous potential for shale gas resources [16]. China has made breakthrough progress in the shale gas exploration and development since 2010, where South China has been identified as the main distribution area of the Lower Paleozoic organic-rich shales. The pinpointed area possesses excellent marine shale gas generation potential [17–19]. The shale gas resource potential in Guizhou Province is tremendous, in which the reserve of shale gas resources is approximately 10.48 trillion cubic meters, according to the preliminary assessment. Northern Guizhou is one of the crucial pilot test areas of marine shale gas resources investigation in China [19,20]. As reported, a high yield shale gas exploration well named Dingye 2HF was deeply drilled in northern Guizhou. Additionally, another shale gas well named Cenye 1 could produce shale gas successfully at 1440–1460 m depth in southeastern Guizhou. It is illustrated that the Lower Cambrian shale gas resources in this area developed through the technical workability and economic efficiency. The innovation is of great significance to change Guizhou Province's reputation as a region that is “short of petroleum and natural gas” [19,20].

Unlike conventional gas reservoirs, the quantification and exploitation of shale gas reservoirs are difficult to assess due to the complex nature of gas storage [5,21–24]. Some critical parameters for assessing reservoir properties have been identified by studies performed in North America. The parameters include effective thickness, total organic carbon (TOC) content, thermal maturity, mineral composition, porosity, permeability and gas content [5,21–27]. These key parameters can not only be used to investigate the reservoir properties of shales, but also provide useful information for the assessment and evaluation of reservoir capacity [5,21–27]. The reservoir conditions have provided a basis for identifying areas with exploration potential [25–27]. Several studies on the shales of the Lower Cambrian Niutitang Formation in northern Guizhou were performed by domestic scholars in the recent years, such as the distribution characteristics, sedimentary environment, organic geochemical characteristics, physical properties of reservoirs, as well as shale gas resource potential evaluation [28–35]. However, the aforementioned studies are still confined. Moreover, the systematic research on accumulation condition and favorable area for evaluation of shale gas from the Niutitang Formation require further investigation. In this paper, the thickness of organic-rich shale, the abundance, type and thermal maturity of organic matter, mineral composition, porosity, permeability, as well as the gas content of shale are examined to assess the regional change trends of the Lower Cambrian Niutitang Formation for marine shale gas accumulation in northern Guizhou. Findings could then determine the most favorable area (sweet spot) for exploration potential of shale gas in northern Guizhou.

2. Geological setting

The northern Guizhou region is located in the northern part of Guizhou Province. The region has an area of $5.44 \times 10^4 \text{ km}^2$,

and it is located in the southwestern margin of the Yangtze platform [29–35]. It is a multiple-cycle sedimentary area that has experienced multistage tectonic movements, including basement forming stage in Wuling-Xuefeng Period, glacial-interglacial stage in Nanhua Period, passive continental margin and steady platform stage in Caledonian, intracontinental-platform stage in Hercynian, steady platform stage in Indosinian, inner continental river sedimentary stage in Yanshanian, as well as inter-mountain faulted and wholesale uplift stage in Himalayan [29–35]. The area's tectonic setting is incredibly complex as it was influenced by previous tectonic movements. The folds are mainly trough-like with an NE or NNE trend. The synclines are narrow and show a close groove-shaped, whereas the anticlines are broad, soothing and are box-shaped. There are very sophisticated fractures with varying directions caused by paleo-faults in northern Guizhou [29–35].

Five main units of shales are deposited in northern Guizhou [35]: the Sinian Doushantuo Formation, the Lower Cambrian Niutitang Formation, the Ordovician Wufeng Formation, the Lower Silurian Longmaxi Formation, and the Permian Qixia-Longtan Formation. The transgression took place due to ice melting and the sea level rising after the Sinian Nantuo Ice Age [35]. Thus, black shale series are widely deposited during the Upper Sinian and Lower Cambrian periods. The Lower Cambrian Niutitang Formation black and carbonaceous shales developed with stable thickness and abundant organic matter, which are the key to marine shale gas exploration in this area.

The sediment environments of the Lower Cambrian Niutitang Formation in northern Guizhou were mainly shallow sea shelf sedimentary facies and deep water shelf sedimentary facies [30]. The lithology of the Niutitang Formation shale in this area varies, which means the main includes dark grey-black and carbonaceous shale, intercalating by stone coal, silicolite, and phosphorite. The lithological association brought by combining the outcrops and cores observation with the measured data as follows: the upper part is gray-dark gray mudstone and sandy shale intercalated by gray-green siltstone; the central part is black mudstone and calcareous shale intercalated by silty sequences; the lower part is black carbonaceous shale, black shale and a small amount of stone coal; lastly, the bottom is silicolite and phosphorite.

The buried depth of the Lower Cambrian Niutitang Formation shale in northern Guizhou is less than 3000 m and it is shallower than 2000 m in most areas [29–35]. The burial depth increased from southeast to northwest, such as 800–1600 m in the Cen Kong-Tongren area or 1800 m of Well Fangshen 1 in southwestern Jinsha [30,31].

3. Accumulation conditions for shale gas

3.1. Shale thickness

The thickness of the Niutitang Formation shales in northern Guizhou fluctuated within the ranges of 30–110 m. The shales were also a belt that was likely distributed from southeast to northwest [29–35]. The shale thickness was over 80 m in the Shiqian–Yuqing–Majiang area and over 100 m in the Yuqing

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