



Original research paper

Main factors for large accumulations of natural gas in the marine carbonate strata of the Eastern Sichuan Basin, China

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Received 12 January 2017; revised 27 February 2017

Available online ■ ■ ■

Abstract

The natural gas accumulation zone, where the marine carbonate rock strata are developed, was formed in the eastern Sichuan Basin under the influence of several main tectonic movements (Caledonian Movement, Indosinian Movement, Yanshanian Movement, and Himalayan Movement). Most natural gas reservoirs exhibit the structural-stratigraphic traps together with multistage accumulation, late-stage adjustment and reformation, et cetera. The natural gas accumulation zone (or so-called gas reservoir groups) is controlled by the following main factors: multi-sourced and multi-formed hydrocarbons for marine source rocks (i.e. Lower Silurian Longmaxi Formation, Lower Permian, Upper Permian Longtan Formation), paleo-uplift, paleoslope, and the hinge belt controlled by the steep dip structures, namely the Lower and Middle Triassic high-quality gypsum. Three sets of high-quality source rocks (i.e. S_{1l} , P_1 , P_{2l}) account for the abundant hydrocarbon supply for natural gas accumulation in the eastern Sichuan area, especially in the destructed oil reservoir formed earlier. The said destructed oil reservoir not only provides the preservation space for natural gas reservoir that will take place later, but it also provides the hydrocarbon source for thermal cracking of hydrocarbons and thermochemical sulfate reduction (TSR). Although the gas reservoirs in the eastern part of the Sichuan Basin experienced multi-stage adjustment and reformation at later times, the thick and high-quality gypsum as well as the mudstone, as available caprocks, have offered a good preservation condition for the underlying gas reservoirs. The paleohighs (e.g. Luzhou paleohigh and Kaijiang paleohigh), the Permian platform margin slope, and the structurally transformed slope under the function of the steep dip anticline in the eastern Sichuan not only form the high-quality carbonate reservoir, but they also became favorable for oil and gas accumulation. The difference in hydrocarbon generation history of the source rock and multistage accumulation of hydrocarbons in the eastern part of the Sichuan Basin caused the diversity in the location of the gas reservoirs, where the gas reservoirs with low H_2S contents are distributed in the eastern Sichuan Basin (e.g. Jiannan gas field), while the gas reservoirs with high H_2S content are located in the northeastern Sichuan Basin (e.g. Puguang gas field). Copyright © 2017, Lanzhou Literature and Information Center, Chinese Academy of Sciences AND Langfang Branch of Research Institute of Petroleum Exploration and Development, PetroChina. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Keywords: Eastern Sichuan Basin; Marine gas reservoir; Source rocks; Carbonate strata; Paleo-uplift; Paleoslope; Gypsum

1. Introduction

The Sichuan Basin is a large marine-continent. It's a superimposed basin with a stable structure and abundant gas

where the marine carbonate sediments are distributed from the Sinian to Middle Triassic. Since the 1950s and 1960s, some large- and middle-sized gas fields have been discovered, such as the Wolonghe gas field (WLH), Weiyuan gas field (WY), and Jiannan gas field (JN) [1]. In recent years, the significant breakthrough of natural gas exploration in the marine carbonate strata of the Sichuan Basin has been obtained. By the end of 2007, the cumulative proven reserves of marine natural gas in the Sichuan Basin were over $13616.5 \times 10^8 \text{ m}^3$. Thus,

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Peer review under responsibility of Editorial office of Journal of Natural Gas Geoscience.

the Sichuan Basin has become recognized as the basin with the largest proven geological reserves of marine natural gas. Specifically, a mass of medium- and large-sized natural gas fields were discovered in the eastern part of the Sichuan Basin, such as the Puguang gas field (PG) [2]. This significant discovery not only gained more attention from domestic and overseas geologists, but it also led to the region becoming a hotspot for marine natural gas exploration. The natural gas in the eastern Sichuan Basin is mainly produced from the Carboniferous Huanglong Formation (C_2), the Upper Permian Changxing Formation (P_{2ch}), as well as the Lower Triassic Feixianguan and Jialingjiang formations (T_{1f} , T_{1j}), which is characterized by various H_2S contents being present in different gas layers [3–5]. Due to the complex oil and gas geological conditions in the study area, high thermal maturity of natural gas, multi-sourced and multi-accumulated hydrocarbons, and late-stage TSR alteration among other factors, the original geochemical characteristics of natural gas have been changed, for example the extremely high dryness coefficient, the isotopically heavier methane, and the reversal pattern of the carbon isotopes between methane and ethane [4,6,7]. A lot of research investigating the gas source, genesis, and gas reservoir types in the eastern part of the Sichuan Basin has been done [1,3–6,8]. It brought about a commonly accepted view that natural gas in the Carboniferous reservoir mainly originates from the Silurian marine source rocks, whereas natural gas in the Permian and Lower Triassic reservoirs is generally considered to be related to the marine source rocks of the Lower Permian, Upper Permian Longtan Formation, and Lower Triassic. On the other hand, studies on the different types of gas reservoirs in the eastern part of Sichuan Basin and the accumulation conditions of natural gas have been paid less attention. In this paper, after the characteristics of typical gas reservoirs in the eastern part of the Sichuan Basin have been contrastively interpreted, we will then discuss the formation of gas reservoirs and accumulation of natural gas in the eastern part of the Sichuan Basin in combination with the hydrocarbon generation history of marine source rocks, gas geochemistry, gas pool formation and preservation conditions. The geochemical evidence for distinguishing the gas source and genesis will likewise be presented.

2. Geologic background

The Sichuan Basin is one of the most important places for commercial gas production in China, and oil and gas exploration in the region has been ongoing since the 1950s. A great number of natural gas fields have been discovered in the basin, with the exception of several small-scale oil fields in the central and southern part of the basin (Fig. 1). The Sichuan Basin, located in the eastern part of Sichuan province, is a large-scale cratonic basin with an area of 23×10^4 km². The present basin is shaped in a rhombus pattern surrounded by a series of mountains. The Sichuan Basin has gone through complicated tectonic movements in its sedimentary history, and some of the important tectonic

movements experienced in the region since the Proterozoic era include the Caledonian Movement ($320 \pm$ Ma), Indosinian Movement (205–195Ma), Yanshanian Movement ($145 \pm$ Ma), and Himalayan Movement (23–3Ma). The sediments in the Sichuan Basin can be as thick as 12 km, with the marine sediments occurring from the pre-Sinian to the Middle Triassic layers in addition to the transition and continental facies being found after the Upper Triassic (Fig. 2). The late Caledonian tectonic movement which occurred during the late Silurian era caused the central palaeohigh to extend towards NE, hence, the interruption of sedimentation [9]. Thus, there is a small amount of sediments in the Devonian, and the Carboniferous strata only developed in the east of the Sichuan Basin [3]. The Indosinian Movement in the Middle-Late Triassic (stage I) and Late Triassic (stage II) resulted in a sediment transformation from marine to non-marine in the Sichuan Basin. The Upper Triassic Xujiahe Formation (T_{3x}) belongs to the terrigenous sediments and is composed of lake fluvial sandstone, thin shale, and locally distributed coal bed. The Jurassic and Cretaceous sediments are composed of terrigenous red sandstone, mudstone, and black shale with a thickness of 2000–5000 m [3]. Prior the Yanshanian Movement, the main movement of the Sichuan Basin presented as a vertical movement without tense horizontal extrusion. Later on, the tectonic movement was characterized by tense horizontal extrusion with a series of fold belts [9]. During the Himalayan Movement, the extrusion from the Pacific Plate caused the Sichuan Basin to be completely uplifted, and a great number of steep dip structures were subsequently formed in the eastern part of the basin.

3. Distribution of marine gas reservoirs and petroliferous features in the eastern part of the Sichuan Basin

To date, 108 natural gas fields have been discovered in the Sichuan Basin, of which 24 large- and medium-sized fields located in the eastern part of Sichuan Basin display a total proven geological gas reserves of about 9465.8×10^8 m³. The natural gas is mainly preserved in the Carboniferous Huanglong Formation (C_2h), Lower Permian Maokou Formation (P_{1m}), Upper Permian Changxing Formation (P_{2ch}), Lower Triassic Feixianguan Formation (T_{1f}), and Jialingjiang Formation (T_{1j}). The trap type of the gas reservoirs is the structural-lithological traps (Table 1), which is characterized by multistage reservoirs and late-stage adjustment. The spatial distribution of large- and medium-sized gas fields in the east of the Sichuan Basin is controlled by the Kaijiang paleo-uplift, Luzhou paleo-uplift, paleoslope, and hinge zones, and all of them were constrained by steep dip structures in the east of the Sichuan Basin. Contrastively interpreting the typical marine large- and medium-sized gas fields (e.g., PG, WLH, JN) in the Sichuan Basin (Table 2) showed that the hydrocarbon source rocks mainly cover three sets of marine hydrocarbon source rocks, namely the Lower Silurian shale, the Lower Permian mudstone and carbonate rocks, and the Upper Permian mudstone and coal measures. The types of reservoir beds mainly consist of brecciated dolomite, oolite

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