PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 43, Issue 3, June 2016
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2016, 43(3): 349–359.

RESEARCH PAPER

Key geological issues and main controls on accumulation and enrichment of Chinese shale gas

GUO Tonglou*

Exploration Company, Sinopec, Chengdu 610041, China

Abstract: By analyzing geological characteristics of shale gas in Southern China and the United States, main factors controlling the accumulation and key issues in the exploration and development of shale gas in China have been examined. The geological characteristics of shale gas in China include multi-stage tectonic evolution, complex structure types, abundant faults, small continuous distribution area of shale formations, and no corresponding relationship between current thermal evolution degree and current burial depth of two main sets of shale formations (the Cambrian and Silurian). According to the analysis of the factors affecting shale gas enrichment such as fracture, tectonic type, shale gas migration, and gas content etc, the enrichment mechanisms of shale gas in China are: "sedimentary facies and preservation condition" are the main reservoir-controlling factors affecting the accumulation of shale gas, and "structure types and tectonism" are the main factors controlling the enrichment of shale gas in China; The former factors define shale gas plays, and the latter ones determine the position of sweet spots. The future research directions of shale gas in China are: firstly, contrary to the shale gas development in the United States, shale gas exploration and development in China should extend from the overpressure to normal pressure, and even low pressure areas; secondly, shale gas exploration in the Sichuan basin should extend from middle-deep to deep formations, studies should be done on the shale gas enrichment mechanism and accumulation models in formations deeper than 4 000 m, and horizontal well fracturing technology for these formations; thirdly, the development of transitional facies and continental facies shale gas should be brought along by drawing on exploration and development experience of marine shale gas.

Key words: Chinese shale gas; tectonism; preservation condition; accumulation and enrichment mechanism

Introduction

In recent years, great progress has been made in the shale gas exploration, development and research in Southern China. In the Sichuan basin, major breakthroughs in shale gas exploration have been made in Upper Ordovician Wufeng Formation-Lower Silurian Longmaxi Formation and Lower Cambrian Qiongzhusi Formation (Niutitang Formation), and a number of shale gas fields have been discovered in these formations, including Fuling, Changning, Zhaotong, Weiyuan, etc. Meanwhile, a number of shale gas exploration wells have been drilled in Sichuan, Chongqing, Guizhou, Hunan, Hubei and other provinces, with a lot of valuable data collected. Shale gas resource assessment has been carried out for Jurassic Formation of Sichuan Basin, Permian Formation of Middle-Upper Yangtze area and Triassic shale of Ordos Basin, bringing about the breakthroughs in shale gas exploration in Jurassic and Triassic Yanchang shale. However, there are no commercial shale gas exploration discoveries except the above mentioned shale gas fields in Sichuan Basin[1–2]. An increasing number of exploration practices show that there are still many special geological issues which need to be solved in the Chinese shale gas exploration and development. Therefore, Chinese shale gas exploration and development can't simply copy the successful exploration and development experiences of the U.S. shale gas, but should innovate the theory and technology of Chinese shale gas exploration according to the geological background of shale gas development in China[3–10].

1. Geological features of shale gas in China

There are neither identical basins nor identical shale gas fields; even in the same basin, different core areas are different in geological elements controlling shale gas enrichment. Comparison of shale gas geology between South China and North America have been made by many researchers[4–7][8–11], but most of which are excessively emphasized on their similarities. The author thinks that more attention should be paid to the geological differences between South China and North America. Rather than shale geological setting, basic geological conditions (organic carbon content, mineral content, ther-

Received date: 24 Dec. 2015; **Revised date:** 14 Mar. 2016.
*** Corresponding author.** E-mail: guotl.ktnf@sinopec.com
Foundation item: Supported by National Major Oil & Gas Project (No. 2011ZX05005-003); Major Oil & Gas Project of Ministry of Land and Resources of the People's Republic of China (No. 2009GYXQ15-06) and Geological Survey Project of China Geological Survey (No. 1212011220758).
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mal maturity, physical properties, etc.), the present shale gas distribution, shale gas preservation and the corresponding structure evolution processes are the main controlling factors leading to the differences in shale gas accumulation and enrichment between China and the U.S. Therefore, "China-style shale gas" is elucidated to show the major shale gas differences between China and the U.S.

1.1. Geology features of US shale gas fields and implication

1.1.1. Geological features

There have been many discussions by predecessors about the geological setting of shale gas development [8, 12–13]. The U.S. Shale gas mainly develops in two kinds of basins, namely foreland basin and craton basin, but the former is dominant. For example, the 5 major shale gas fields, Marcellus, Haynesville, Fayetteville, Woodford and Barnett, came into large-scale exploration and development after 2004 are all located in foreland basins; out of the 5 shale gas fields put into exploration and production in 1980 s-1990 s, three, Devonian Ohio Gasfield, Mississippian Barnett Gasfield and Cretaceous Lewis Gasfield, are located in foreland basins too, and only 2, namely Devonian Antrim Gasfield and New Albany Gasfield, are located in craton basins.

Geological features of the U.S. shale gas can be summarized as follows: (1) characterized by many shale gas basins, shallow burial and extensive distribution, American's shale gas developed mainly in over 50 basins of 20 states, with the technically recoverable resources of about 28×10^{12} m^3 [8]; (2) found in multiple series of strata, the shale in the US is of large thickness, high quality, and marine facies; (3) thermal evolution level changes greatly in a same basin, taking the Marcellus Shale in the Appalachian Basin as an example, its R_o varies from 2% in the depression region to less than 0.5% in the slope region, and positively correlates with present buried depth[14]; (4) the shale formations have wide span of pressure coefficient, from underpressure, normal pressure and overpressure, the 5 big gas fields put into exploration and production before 2004 are all of underpressure and normal pressure, while the 5 gas fields put into exploration and production later are mostly of overpressure; (5) distributed in stable structures, the shale is continuous and large in area; (6) the percentages of the effective pores are high, most of which are more than 5%.

1.1.2. Implication

(1) The U.S. shale gas exploration and development started from abnormal underpressure gas fields, and practice has proved that abnormal underpressure gas fields can also reach long-term stable production. For example, the shale gas production of Ohio Gasfield in 1981-1999 had been kept at $(28.3–36.8)\times10^8$ m^3/a; discovered in 1914, Big Sandy Gasfield located in Appalachian Basin with the Upper Devonian Ohio Shale as major pay is also an underpressure gasfield, and has produced over 707.9×10^8 m^3 of shale gas[15].

(2) National support to basic research promotes shale gas development. In 1970s, the U.S. Department of Energy initiated the eastern shale gas program, spanning over 16 years, the program had covered geology, geochemistry, geophysical properties, and simulation of hydraulic fracturing, chemical blasting fracturing, and directional drilling etc, and accumulated a large number of reports, articles, reviews and database, which have greatly promoted the expansion of Big Sandy Gasfield to the central and southwestern parts of West Virginia and the southeastern part of Ohio[14].

(3) Successive technological innovations guarantee the rapid development of shale gas. The rapid US shale gas development benefits from several major technological progresses. The Eastern Gas Shale Project initiated by the U.S. government led to major breakthroughs in shale gas geology and development technology during the mid-late 1980s, and the surging of shale gas production[16]. In 1997-1999, shale gas reservoir stimulation technologies reached mature; from 2002, horizontal well drilling has been widely applied in shale gas development, making shale gas production soar up[11]. Subsequently, the shale gas exploration and development has extended from shallow to deep strata (abnormal underpressure, normal pressure to overpressure shale gas field), with a batch of shale gas fields with overpressure strata, high production and large-scale reserves discovered, including Marcellus, Haynesville, Fayetteville, etc. The U.S. shale gas production achieves has rapid increased since 2007. The U.S. annual shale gas production rose from 196×10^8 m^3 in 2004, to 311×10^8 m^3 in 2006, $1\,378\times10^8$ m^3 in 2010, more than $1\,970\times10^8$ m^3 in 2011, $2\,300\times10^8$ m^3 in 2012 and up to $3\,637\times10^8$ m^3 in 2014[8, 17].

(4) Argument not sticking to definition – natural gas produced from shale is considered as shale gas. The U.S. commercial natural gas industry began in 1821, marked by a gas discovery with an 8.2 m deep well in Devonian shale of Chautauqua County, New York. Without other treatments in the well, it is speculated that there are well-developed fractures in the reservoir. There has been seldom argument over whether the produced gas is fracture shale gas or shale gas, whether there are siltstone and carbonate interlayers, and whether the gas produced from the interlayers is conventional gas or shale gas.

1.2. Geological features of shale gas in China

Southern China is the major region for shale gas exploration, and Sichuan Basin and its peripheral areas are the favorable areas for shale gas exploration breakthrough and commercial development. Therefore, the Qiongzhusi and Wufeng-Longmaxi Formations in Sichuan Basin and its adjacent areas are taken as key formations to analyze the geological features of shale gas development and preservation in China.

1.2.1. Depositional features

Different from the US where major shale strata are in foreland basin, Qiongzhusi and Wufeng-Longmaxi shale formations in Sichuan Basin and its peripheral areas are all in Yangtze craton basins.

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