Available online at www.sciencedirect.com
ScienceDirect
Journal of Natural Gas Geoscience xx (2017) 1−16
http://www.keaipublishing.com/jnggs

Original research paper

Geological characteristics, main challenges and future prospect of shale gas

Caineng Zou [a,b,*], Qun Zhao [a,b], Dazhong Dong [a,b], Zhi Yang [a], Zhen Qiu [a,b], Feng liang [a,b], Nan Wang [a,b], Yong Huang [c], Anxiang Duan [a], Qin Zhang [a], Zhiming Hu [a]

[a] *Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China*
[b] *National Energy Shale Gas R&D (Experimental) Center, Langfang 065007, China*
[c] *Southwest Petroleum University, Chengdu 610600, China*

Received 30 September 2017; revised 24 October 2017
Available online ■ ■ ■

Abstract

The development of shale gas in the United States has made a breakthrough, profoundly changed the pattern of oil and gas supply. It created the "shale gas revolution" on a global scale. Based on the practice of shale gas development in China and abroad, this paper aims to: (1) Summarize 5 basic characteristics, which are shale gas resource distribution, reservoir space, sweet spot area (section), hydrocarbon type and development mode. (2) Divide China shale development into three stages: scientific exploration, technological breakthrough and mature development. The United States is divided into three stages: scientific exploration, technological breakthrough and mature development. The United States is divided into three stages: scientific exploration, technological breakthrough and mature development. (3) Identify 4 challenges in the future development of China shale gas industry. It includes non-marine shale gas potential, core technology and equipment for resource deep than 3500 m, complex surface "factory mode" production, human geography and other non-technical factors. (4) Process economic evaluation under the conditions of government financial subsidies. China's shale gas project FIRR is about 8.0%−9.0%. Considering the global shale gas resources, consumer demand and other factors, it global shale gas production is expected to reach 1.1 × $10^{12}m^3$ by 2040.

Keywords: Shale gas; Black shale; Shale gas revolution; Nano pore; Sweet spot area; Sweet spot section; Artificial gas reservoir

1. Introduction

After the US made a breakthrough in the development of shale gas, with the aid of core technologies including horizontal well volume fracturing, micro-seismic surveillance and multi-well pad based exploitation to constantly promote the development of tight gas and rapid increase in the output of unconventional oil and gas, a worldwide "Shale Gas Revolution" has been brought about in energy sector. Shale is fragile fine grained sediment layer [1] with shaly or lamellar bedding composed of clastic grains with grain size smaller than 0.0625 mm and clay together with organic substance. The shale in conventional oil and gas system has been considered as "an iron plate" without pore space and taken as source rock or cap-rock factor [2]. Since a breakthrough made in shale gas development in Barnett in 1997, a number of shale gas has been developed in Haynesville, Marcellus and Utica in succession [3], it is known as a common knowledge that pore space of shale contains rich natural gas resource and that more and more attention has been paid to shale gas as a key natural gas resource. China is also abundant in shale gas resource [4,5], having taken shape in production and size and become the largest shale gas production area in addition to those in North America after 10 years of development.

* Corresponding author. Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China
E-mail address: zcn@petrochina.com.cn (C. Zou).
Peer review under responsibility of Editorial office of *Journal of Natural Gas Geoscience*.

https://doi.org/10.1016/j.jnggs.2017.11.002

Please cite this article in press as: C. Zou, et al., Geological characteristics, main challenges and future prospect of shale gas, Journal of Natural Gas Geoscience (2017), https://doi.org/10.1016/j.jnggs.2017.11.002

Discrepancy between shale gas and conventional natural gas in terms of forming condition and distribution characteristic has enriched traditional natural gas reservoir theory and improved level of technology for exploration and development to a certain extent, "shale gas revolution" plays a landmark role in promotion of development in oil and gas geology and update and upgrade of oil and gas industry. The paper summaries basic characteristic of shale gas and divides stages of development and recognition of shale gas field based on detailed analysis of typical shale gas fields in China and the US and determines challenge to development of shale gas in China inspired by "shale gas revolution" and draws a comparison of economical efficiency in shale gas development between China and the US as well as analyzes and predicts prospect for development of shale gas.

2. Basic characteristics of shale gas

Oil and gas in black shale bed series contain proximal tight oil, shale oil and gas as well as coal crevice gas as 3 types of unconventional oil and gas, the exploitation of tight oil and shale oil depends mainly on the output of dissociated oil and the exploitation of tight gas, shale gas and coal crevice gas depends mainly on continuous output of dissociated and adsorbed gas (Table 1).

According to the division by United States Geological Survey [6], gas-bearing shale system is typical unconventional natural gas system, being continuous natural gas accumulation. Curtis [7] defined shale gas as biogenic gas, thermogenic gas or multi-genetic gas continuously distributed in rich organic shale system characterized by full of gas, continuous distribution in large area, multi-lithology trap and shorter migration distance. Zou [8] defines shale gas as natural gas contained in organic-rich shale in dissociated state and adsorbed state in most cases, being authigenic reservoir and continuous accumulation of natural gas in large area. The paper defines shale gas as natural gas generated from and subjected to continuous accumulation in organic-rich black shale, with numerous and abundant nanoscale pores in shale reservoir serving as primary reservoir space. It is necessary to locate "sweet spot area"for development of shale gas field to achieve effective development by fracturing "sweet spot section "to ensure "artificial permeability". Gas bearing shale beds are characterized by continuous distribution in large area, lamina and bedding in widespread development, abundant nanoscale organic pores, "sweet spot area (section)"enrichment, thermogenic free gas as decisive factor to determine output, high output to be achieved by control of natural fracture density and over pressure development degree and development of "artificial shale reservoir" as horizontal well fracturing network, which are considered as 7 basic characteristics.

2.1. Continuous distribution of shale gas in large area

Shale gas reservoir integrating source and storage is subject to continuous distribution in large area along slope and depression zone, being large in resource extent. The natural gas contained in reservoir after hydrocarbon generation and expulsion by organic substance in shale is to form shale gas accumulation, shale is not only source rock but also reservoir. The accumulation in authigenic reservoir makes shale reservoir in continuous distribution become one of the main control factors for distribution of shale gas fields, it is common that shale gas is in continuous distribution in large area along slope and depression zone. Barnett shale gas is taken as an example: it is observed that shale reservoir is in wide distribution along slope zone in Ouachita mountainous region [9], with transverse continuous distribution up to more than 2000 km^2, gas-bearing area of about 1.55×10^4 km^2, and technical recoverable reserves up to 7362×10^8 m^3 [10].

2.2. Widespread development of lamina and bedding

Bedding development has significantly improved the horizontal seepage capability of shale reservoir and enhanced output of shale gas well. Shale as pulveryte is under the combined action of physical, chemical and biological processes in sedimentation period to form sedimentation of lamina different in component, including brittle mineral (calcite and dolomite etc.), clay mineral (illite and illit/smectite interstratifications) and organic substance (algae etc.), with bedding (seam) developed between laminas in continuous or intermittent distribution and combination of similar laminas to form lamina group and further form single layer with horizontal bedding (seam) in development and continuous distribution in most cases [11]. It is observed from research that lamina and bedding (seam) are able to communicate inorganic mineral pores and nanoscale organic pores in shale reservoir to form high speed channel [12,13] for horizontal migration of oil and gas. Bedding is in widespread distribution in gas bearing shale in Wufeng Formation-Longmaxi Formation in Sichuan Basin, with its horizontal permeability higher than $0.01 \times 10^{-3}\mu m^2$ (average value is $1.33 \times 10^{-3}\mu m^2$), being much higher than its vertical permeability in similar depth (lower than $0.001 \times 10^{-3}\mu m^2$, average value is $0.0032 \times 10^{-3}\mu m^2$), the difference between which is more than three orders of magnitude [14]. Gas bearing shale is compacted along vertical upward direction, with vertical permeability on the low side to prevent shale gas from rapid dissipation and make for preservation, however, horizontal bedding (seam) development has greatly improved horizontal seepage capability of shale reservoir [15] and is able to make horizontal well more likely to form complex fracture network [16,17] after transformation by hydraulic fracturing to enhance output of shale gas.

2.3. Abundant nanoscale organic pores

Shale reservoir is compacted, with development of nanoscale pore throat volume and organic pores in most cases, and the nanoscale pores are the main volume for gas accumulation. The shale reservoir is super compacted, with pore diameter from 50 mm to 100 mm and permeability from 10^{-9} to $10^{-3} \times 10^{-3}\mu m^2$ (Table 2). A number of analyses and test data show that nanoscale pore and pore-throat volume are in

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