PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 44, Issue 4, August 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2017, 44(4): 675–685.

RESEARCH PAPER

Progress and development trend of unconventional oil and gas geological research

SONG Yan[1, 2], LI Zhuo[1,*], JIANG Zhenxue[1], LUO Qun[1], LIU Dongdong[1], GAO Zhiye[1]

1. State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China;
2. Unconventional Oil and Gas Collaborative Innovation Center, Northeast University of Petroleum, Daqing 163000, China

Abstract: The progress in pore structure characterization, hydrocarbon occurrence state, mechanism of oil and gas accumulation, main controlling factors and high production model of unconventional oil and gas is reviewed. The unconventional oil and gas geological research developed from observation of the nanopores to quantitative full scale and 3D pore structure characterization, from macroscopic occurrence state study to microscopic occurrence state evolution discussion, from differential pressure drive and preferential channel migration to staged accumulation and wettability preferential migration, from accumulation controlled by source to accumulation jointly controlled by source-reservoir assemblage and preservation conditions, from accumulation model to enrichment and high production model, revealing the research progresses and future trends of unconventional oil and gas geology. Challenges are presented in unconventional oil and gas geological theory, enrichment conditions and recoverable resources potential of deeply buried unconventional oil and gas, combination of unconventional oil and gas geological research and engineering technique, and basic geologic research for joint mining of different unconventional oil and gas resources.

Key words: unconventional oil and gas; geological theory; research progress; development trend; issues and challenges

Unconventional oil and gas resources have great potential in China, so development of unconventional oil and gas can relieve the contradiction between the supply and demand of oil and gas[1–4]. Based on summary of the research progresses, this paper focuses on the tendency of unconventional oil and gas geological research and points out the issues and challenges in current unconventional oil and gas exploration and development.

1. Trend of unconventional oil and gas geological research

Unconventional oil and gas in this paper refers to tight oil and gas, shale oil and gas and coalbed methane (CBM). In recent years, unconventional oil and gas research has witnessed rapid progress, especially in pore structure characterization, occurrence state evaluation, accumulation mechanism and primary controlling factors, and enrichment and high-yield models, which has boosted the exploration and development of unconventional oil and gas. Therefore, it is of great significance to understand the development trend of unconventional oil and gas geological research.

1.1. Pore structure characterization of unconventional reservoirs

Pore structure is the basis of studying the occurrence, accumulation mechanism and resource potential of unconventional oil and gas. Unconventional reservoirs are tight with low porosity and ultralow permeability, therefore, it is very difficult to characterize their pore structure with conventional techniques[5]. High-resolution scanning electron microscopy (SEM) had not been applied to the study of shale reservoir, and pore characteristics of shale had been rarely reported before 2009. With the discovery of nanopore in shale for the first time in 2009, the micro-nano pore structure of shale has been established[6–8]. Pore size distribution (PSD) of tight sandstone and tight limestone was studied by mercury porosimetry[9–12]. It was found that PSD of the Upper Cretaceous tight sandstone in the Great Green River Basin was 0.06–10.00 μm, with a single peak at around 600 nm[12–13], and the pore diameter range of tight sandstone in the Ordos Basin is 0.1–200 μm, with a peak at about 400 nm[14]. However, unable to detect pores smaller than 100 nm in diameter in shale[15], this technique cannot give a full picture of the pores in unconven-

Received date: 09 Jan. 2017; **Revised date:** 17 May 2017.
*** Corresponding author.** E-mail: zhuo.li@cup.edu.cn
Foundation item: Supported by the China National Science and Technology Major Project (2017ZX05035-002); National Natural Science Foundation of China (41502123).

tional reservoirs. Since 2012, full-scale PSD characterization and three-dimensional reconstruction techniques have been applied to shale[16], making it possible to find out the sizes of all pores (1 nm to 200 nm) and 3D structure of micro-nanopores[17]. Hence, pore structure characterization of unconventional reservoir has evolved from observation of nanopore to quantitative full scale and 3D pore structure characterization.

1.1.1. Characterization of full-scale pore structure in unconventional reservoirs

As pores in unconventional reservoirs cover a wide size range from nanoscale to millimeter scale, the pore structure of unconventional reservoir cannot be fully characterized by a single method[16]. Researchers in China[18–19] combined high-pressure mercury porosimetry (characterizing pores of 80–200 000 nm), low pressure N_2 and CO_2 adsorption (characterizing pores of 1–200 nm and 0.3–1.5 nm) methods to get the full-scale pore size distribution of organic shale. Thanks to this method, it has been made clear that the marine shales in the Silurian Longmaxi Formation of the Sichuan Basin have pore size peaks at 2–3 nm, 70–90 nm and 200–300 nm (Fig. 1a); the transitional shales in the Huaibei coal field have pore size range of 1–200 000 nm, and multiple peaks at 6–20 nm and 400–500 nm (Fig. 1b); and the lacustrine shales in the Ordos Basin have a pore size range of 1.5–20 000.0 nm, and pore size peaks at 1–4 nm, 10–20 nm, 1 000–1 800 nm and about 10 000 nm (Fig. 1c)[20].

Research in the future should focus on effective test range of fluid injection method, and improvement of the full-sized pore structure characterization method, and strength comparison and corroboration with scanning electron microscopy, CT scanning and nuclear magnetic resonance results, to better understand pore structure characteristics of unconventional reservoir.

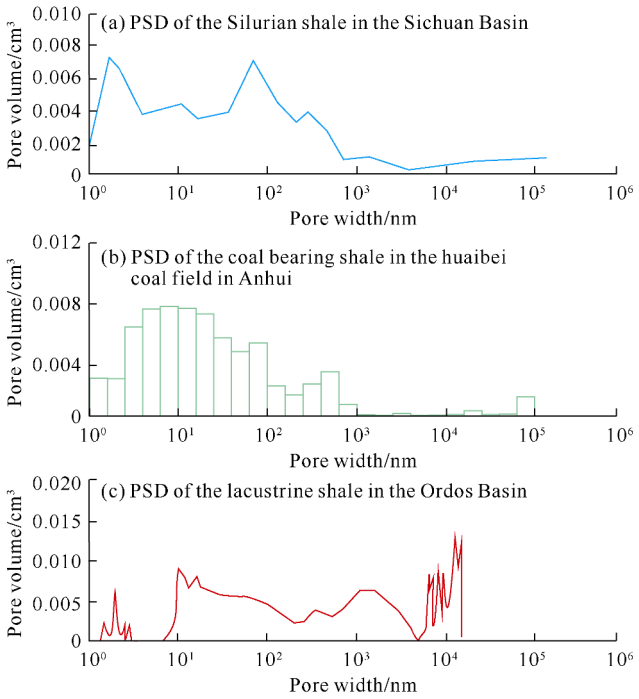

Fig. 1. Full-scale pore size distribution (PSD) of typical shales.

1.1.2. Reconstruction of 3D pore structure in unconventional reservoirs

3D pore structure can show the spatial distribution, proportion and pore connectivity of different types of pores in unconventional reservoir[21–23], and is of great significance for finding out the occurrence, mobility and resources of unconventional oil and gas. Since 2012, focused ion beam scanning electron microscopy (FIB-SEM) and X-ray tomography (micro CT and nano CT) have been used in this research field, giving us deeper insight into the 3D pore structure characteristics of unconventional reservoir[24–25]. In 2016, with resolution enhancing to less than 10 nm, FIB-SEM enables the 3D reconstruction of spatial distribution of minerals, organic matter and pores in shale from 6.7 nm to 7.7 mm[26]. Ma et al.[26] revealed that organic matter pore in shale was mainly around 40 nm in diameter, the intergranular pore was 200 nm, and organic matter pore and intergranular pore in clay minerals, in good connectivity, are the major storage space and migration pathways of shale gas.

The development trends are: (1) optimization of experimental setup and parameter extraction to further improve the resolution of three-dimensional reconstruction in microscopic aspect; (2) increasing sample size and enlarging the scope of characterization to overcome the effect of heterogeneity to enhance the representation of 3D pore structure characterization.

1.2. Occurrence state of unconventional oil and gas

Unlike conventional gas occurs mainly as free gas, gas can be absorbed in unconventional reservoirs, therefore, free gas and adsorbed gas exist in coal and shale reservoirs. The adsorbed gas adheres in a single layer or multiple layers to the inner surface of pore, while the free gas fills in the middle of pores[27–29]. Early studies showed the adsorbed CBM accounted for 80% of the total gas content founding coal reservoirs, while adsorbed gas can be 20%–85% of the total gas content in shale reservoirs, and high shale gas layers mainly produce free gas[30–35]. Ji et al.[36–37] restored transformation process of shale gas occurrence states according to tectonic evolution in 2014. In 2016, high-resolution SEM and molecular dynamics simulation were applied to shale gas research, to reveal the microscopic occurrence of shale gas[38]. These show occurrence study of unconventional oil and gas has evolved from macroscopic and static characterization to microscopic, dynamic evolution research.

1.2.1. Microscopic characteristics of unconventional oil and gas occurrence

Accurate characterization of hydrocarbon occurrence in micro-nanopore throat is of great significance to find out unconventional oil and gas enrichment mechanism and resource