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Research Article

New progresses in basic geological theories and future exploration domains of natural gas in China[☆,☆☆]

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Abstract

As natural gas exploration expands to deep, ultra-deep and unconventional areas, more and more complex exploration targets are encountered. In this circumstance, it is necessary to improve the existing basic natural gas geological theories for guiding the exploration and discovery of more giant gas fields. In this paper, the researches on basic natural gas geological theories since the beginning of the 12th Five-Year Plan were engaged, and then the key exploration target zones were analyzed. Some results were obtained. (1) The theory of whole-process hydrocarbon generation of organic matters was improved and the geologic theories of organic matter hydrocarbon generation (e.g. the thermal evolution model of kerogen degradation and the successive gas generation of organic matters) were developed. (2) Multi-element natural gas genesis identification method, quantitative evaluation method for different types of seals/caprocks, tight sandstone gas accumulation theory for low hydrocarbon generation intensity region, and hydrocarbon accumulation theory for giant ancient carbonate gas field were established, and the geological theories of gas generation, genesis identification and hydrocarbon accumulation were developed to provide the effective guidance for the exploration breakthrough and discovery of giant gas fields in the key basins of China recently. Four conclusions were reached: (1) ancient carbonate rock, tight sandstone, foreland region, shale and volcanic rock are primary exploration targets for discovering giant gas fields; (2) craton and foreland basins are still the key exploration areas, and ancient uplift, gentle slope and thrust belt are the main enrichment zones; (3) ancient strata and deep formations are critical gas exploration targets in the future; (4) oil cracking gas in marine basins, tight sandstone gas and shale gas are the important replacement resources for future gas reserves and production growth.

Keywords: Natural gas; Basic geological theory; New progress; Exploration domain; Ancient carbonate rock; Tight sandstone; Craton; Foreland basin; Giant gas field

Natural gas is a kind of green energy resource. It may generate much less pollution than oil and coal when burning to produce the same quantity of heat. In 2016, the proportion of natural gas in China's energy resources structure was only 6.4%, far below the world average (25%). Through multiple rounds of national researches on natural gas technology and projects, fruitful results have been achieved in natural gas-related basic theories, including natural gas generation, genetic identification and accumulation [1–12]. These results have effectively promoted major discoveries and rapid growth of natural gas exploration in the main gas-bearing basins of

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China, and played an important role in promoting the rapid development of China's natural gas industry. Since the 12th Five-Year Plan, China's natural gas exploration has achieved great progresses in conventional carbonate gas reservoirs, tight sandstone gas reservoirs and shale gas reservoirs, and found some giant gas fields (e.g. Anyue, Keshen, Fuling and Changning) [13–22], thus providing a strong support for the rapid growth of domestic natural gas reserves and production. Researches on natural gas technology have played an important role both in the discovery of giant gas fields and the rapid growth of natural gas reserves. Coal-formed gas and oil-cracking gas fields contribute more than 90% of the proved reserves increment of natural gas in China. Currently, four large gas provinces at the level of 1×10^{12} m^3 natural gas reserves and five medium gas provinces at the level of 0.5×10^{12} m^3 natural gas reserves have been formed, with a robust trend of development. By the end of 2016, the total proved geologic reserves of natural gas in China were 11.7×10^{12} m^3, among which 83.4% was distributed in giant gas fields. During the 12th Five-Year Plan, annual growth of natural gas reserves was more than 7000×10^8 m^3 [23]. With the sustained and rapid development of national economy, the contradiction between natural gas supply and demand is more prominent, and the energy gap is expanding. In 2017, China's natural gas consumption was about 2400×10^8 m^3, and production was around 1470×10^8 m^3, thus the gap between supply and demand was more than 900×10^8 m^3. In this circumstance, it is urgent to accelerate natural gas exploration in order to adapt to the economic and social development. However, as natural gas exploration expands to deep, ultra-deep, deep water and unconventional areas, more and more complex exploration targets are encountered. The existing theories of natural gas geology cannot meet the needs of current natural gas exploration. Accordingly, it is necessary to improve the existing basic natural gas geological theories for guiding the exploration and the discovery of more giant gas fields. In this paper, the researches on basic natural gas geological theories were conducted and then the key exploration target zones were analyzed. The study results are significant in improving the existing basic natural gas geological theories, and assuring the sustained, fast and efficient development of natural gas in China during the 13th Five-Year Plan. Moreover, the study results are of great practical implications for building a clean, low-carbon, safe and efficient energy system and protecting the ecological environment.

1. New progresses in basic geological theories on natural gas

1.1. Theory of whole-process hydrocarbon generation of organic matters

The Tissot's hydrocarbon generation mode [24] by later kerogen degradation ever plays an important role of guidance in oil and gas exploration. However, with the expansion of natural gas exploration to deep, ultra-deep and unconventional areas, the Tissot's theory [24] and traditional natural gas geological theories cannot be applied to solve many problems in natural gas exploration in China, such as hydrocarbon expulsion efficiency (retained hydrocarbons) evolution, cracking gas quantity during high maturity stage, hydrocarbon generation threshold, lower limit of natural gas preservation, and identification of gas sources in deep and complex strata (such as the identification of gas from kerogen and cracked oil, the cracking gas of accumulative type and dispersive type). Zhao Wenzhi et al. [3,4,9] established the successive gas generation mode of deposited organic matters, and pointed out that the successive gas generation process in deposited organic matters includes biogas, immature transitional zone gas, kerogen degradation gas and liquid hydrocarbon cracking gas. They thought that the liquid hydrocarbon cracking gas during high- to over-mature stage and kerogen degradation are successive in time and contribution, and the history of thermal evolution and hydrocarbon generation of marine source rocks are much longer and have more total resources than that in previous cognitions. They also revealed the position of disperse liquid hydrocarbon accumulation [12]. For further improving the hydrocarbon generation theory by organic matters, on the basis of the classical Tissot's hydrocarbon generation mode by kerogen degradation and the successive gas generation mode of organic matters, the simulation experiment of hydrocarbon generation and expulsion in a semi-open system and the simulation experiment of gold tube hydrocarbon generation in a closed system were conducted during the 12th Five-Year Plan to deeply analyze the whole-process hydrocarbon generation of source rocks, hydrocarbon expulsion efficiency, retained hydrocarbon quantity, natural gas source at high- to over-mature stage, and cracking temperature of methane homologues. As a result, the whole-process hydrocarbon generation mode of organic matters was established.

1.1.1. Whole-process hydrocarbon generation mode of sapropel organic matters

(1) The retained hydrocarbon quantity in source rocks during evolution stages was calculated, and a quantitative evaluation model of retained hydrocarbons was established. It is confirmed that there are about 20% retained hydrocarbons during high- to over-mature stage. Moreover, the retained hydrocarbon quantity and cracking gas quantity of major source rocks during various stages in some main basins were calculated, which can effectively guide the marine natural gas exploration in deep strata.

(2) By using the autoclave system and the HTHP closed gold tube system, the simulation experiments were performed on natural gas generation of sapropel type kerogen (the shale in the Xiamaling Fm, Qingbaikou System) and from crude oil. By studying the whole-process hydrocarbon expulsion efficiency of sapropel type kerogen, relative ratios of retained hydrocarbons, liquid hydrocarbons outside source rocks and cracking gas in liquid hydrocarbons (with the hydrocarbon expulsion efficiency of 40–60% at oil generation peak)