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Research Article

Distribution laws of large gas fields and further exploration orientation and targets in China☆,☆☆

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Abstract

With the rapid expansion and extension of natural gas exploration and development, it is more and more difficult to discover large-scale reserves in China. To intensify the research on new natural gas exploration domains, we reviewed the progress and trend of natural gas exploration and analyzed the main areas with large-scale proved gas in place (GIP). Then, based on a statistic analysis of large gas fields in China as well as their hydrocarbon accumulation characteristics, their genetic systems were classified and each system's distribution law was also identified. Some research results were obtained. First, carbonate paleo-uplifts of cratonic basins, tight sandstones of extensive gentle slopes and thrust structures of foreland basins are the main areas with large-scale proved GIP in China. Second, there are five genetic systems for large gas fields, i.e. cratonic rift and paleo-uplift (A), stable slope of low-angle open lake (B), thrust structure of piedmont fault depression (C), faulted uplift and igneous rock of intracontinental pull-apart fault depression (D), and anticline structure of epicontinental strike–slip fault depression (E), and one genetic system (F) for unconventional gas, i.e. adsorption and accumulation in nano-scale space. Third, there is one core genetic system for large conventional gas fields in each geologic cycle. Fourth, two-level accumulation, i.e. no migration inside the source and large-scale transportation termination, exists in each single genetic system, and sequential accumulation is formed under the control of multiple factors in the areas where multiple genetic systems are superimposed. Fifth, the multi-system superimposed area is rich in large gas fields and the multi-stress hinge zone in the central area is the natural gas convergence zone. Finally, the future orientation and targets of natural gas exploration in China were pointed out. First, the system A includes Sinian–Lower Paleozoic in the Sichuan Basin, Cambrian in the Tarim Basin and Cambrian–Ordovician in the Ordos Basin. Second, the system C includes the transform zone of Kuqa thrust structure, the northwestern Sichuan Basin and the southwestern Tarim Basin. Third, the system E includes the basins in the eastern China seas. Fourth, the system F includes organic-rich shales in South China and deep coal beds in the Ordos Basin in central China.

Keywords: China; Large gas field; Distribution law; New area; Cratonic rift and paleo-uplift; Thrust structure of piedmont fault depression; Anticline structure of epicontinental strike–slip fault depression; Adsorption and accumulation in nano-scale space

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0. Introduction

Since the beginning of the 21st century, China has obtained fruitful results in natural gas exploration and development, but domestic natural gas supply is still in a very tough situation, partially caused by the difficulties in increasing reserves and production. As natural gas exploration expands, new orientation and domains for seeking scale reserves will become the top priority in the future. After 2000, the geological theory and exploration and development technology of natural gas have advanced in a leap-forward way in China, helping uncover the domains such as ancient marine carbonate rocks and shale, and Mesozoic–Cenozoic continental tight sandstone, deep to ultra-deep structures, and coal seams in sedimentary basins. A large number of large and super large conventional and unconventional gas fields have been discovered and established, including Keshen, Sulige, Anyue, Yuanba, and Jiaoshiba. These results strongly support the rapid growth of reserves and production of natural gas in China. The first 17 years of the current century witnessed an average annual increase of 299.8×10^8 m^3 proved gas in place (GIP) and 66.3×10^8 m^3 gas production, which is equivalent to the discovery, exploration and construction of a large gas field every year. In 2000–2016, the annual newly-increased proved GIP was four times that in the 1990s. In 2016, gas production was five times that in 1999.

In spite of the rapid progress of exploration and development, the situation of gas supply is still pressing in China. According to the statistics issued by National Development and Reform Commission ("NDRC"), China's dependence on foreign natural gas increased from 15.9% in 2000 and 39% in 2017. Therefore, under the current situation where more and more complex targets are encountered and the exploration coverage is increasing, it is of pivotal importance to highlight new domains of natural gas exploration. In this paper, the formation, distribution and exploration potential/practices of actual large gas fields were analyzed, and then the new orientation and domains for future gas exploration were proposed in order to provide references for the reserves and production increase of natural gas.

1. Progress in natural gas exploration

In China, conventional and unconventional natural gas has been developed side by side since 2000. A series of theories and technologies have been formed with regard to conventional domains like deep clastic rock, carbonate rock, volcanic rock, and sea waters, and unconventional domains like tight gas, shale gas, and coalbed methane, and a large number of large gas fields have been discovered and confirmed, thereby facilitating the rapid growth of proved GIP.

The theory of hydrocarbon generation was developed and more understanding was made on resources. The mode of gas generation in highly-evolved coal-measure source rocks was established; it is clarified that the R_o cutoff for gas generation in coal-measure source rocks extends from 2.5% to around 5.0%, and additional natural gas (more than 20%) can be generated when R_o = 2.5–5.0% [1]. The mode of gas generation by crude oil cracking in reservoirs and of residual hydrocarbon in source rocks was established, indicating that the gas generated by sapropel kerogen accounts for 20–25%; it is clarified that kerogen is mainly cracked to generate gas when R_o = 1.3–2.5%, and the gas generated when R_o >2.5% accounts for 5%. As is estimated, the cracking gas in the Sinian formations in the Gaoshiti–Moshi area, the Sichuan Basin, is 37.5×10^{12}–45.6×10^{12} m^3, and that in the Lower Cambrian Longwangmiao Formation is 18.9×10^{12}–26.1×10^{12} m^3.

In terms of deep marine carbonate exploration, some innovative accumulation theories and knowledge were obtained, including "four ancients" (ancient intracraton rift, ancient inherited uplift, ancient shoal and beach reservoir, and ancient source kitchen dominated by in-situ oil cracking) for ancient carbonate rocks, and "one reservoir in one reef" for reef bodies [1–4]. Some key exploration and appraisal technologies were developed, such as gravity–magnetic–electric–seismic-based geophysical interpretation for deep structures, and quantitative characterization, prediction and gas-potential detection of carbonate pore-vug reservoirs. A batch of large gas fields (reservoirs) were discovered and proved, including Anyue, Puguang, Yuanba, Tazhong, and Longgang. Typically, some risk exploration wells (e.g. Gaoshi 1) achieved significant breakthroughs, ushering the discovery and confirmation of the Anyue gas field. At the end of 2017, the proved GIP was 8485×10^8 m^3 in the Anyue gas field, recording as a monoblock ancient carbonate gas field with the largest reserves domestically.

In terms of tight gas exploration, the accumulation theory of "alternating reservoir–source superposition, transportation via pore/fracture network, and high-efficient accumulation near source rock" was proposed, and some key technologies were developed, such as banded non-longitudinal seismic survey in loess layers, multi-wave seismic acquisition and processing, pre-stack seismic prediction of reservoir, identification of tight gas layer, horizontal well drilling, and horizontal well multi-interval and multi-stage fracturing [5–8]. The Sulige gas field was discovered and confirmed in the Ordos Basin, and the exploration coverage in the Sulige area was expanded towards east, south and west to nearly 6×10^4 km^2, forming a large gas province with reserves of more than 4×10^{12} m^3. Meanwhile, multiple gas zones with a magnitude of 100 billion cubic meters of natural gas reserves (e.g. Daniudi and Shenmu) and the Upper Triassic Xujiahe Formation gas zone with reserves of nearly 1×10^{12} m^3 were discovered and proved. The total newly-increased proved GIP amounted to 4.4×10^{12} m^3, accounting for 45% of the total proved GIP in the same period.

In terms of deep foreland exploration, the accumulation theory of continuous and intense charging of hydrocarbons under overpressure in subsalt formations of thrust belt was proposed, and some key technologies were developed, such as wide-line large-array seismic acquisition and pre-stack depth migration processing and interpretation for deep formations in complex mountains [9,10], and oil testing, completion and reservoir stimulation of ultra-deep gas wells with ultra-high