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Original research paper

Status and prospects of deep oil and gas resources exploration and development onshore China☆

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Abstract

Many significant breakthroughs have been made in regards to deep oil and gas exploration and development in recent years. However, a systematic analysis has not been carried out on the progress, challenges, and development trend of exploration and development of onshore deep oil and gas resources in China. This paper summarizes five main points of deep oil and gas resources: (1) more gas, less oil, and complicated phases; (2) high temperature and pressure, as well as profoundly different basins or formations; (3) multiple hydrocarbon sources and accumulations; (4) relatively tight but effective large-scale reservoirs; and (5) complicated accumulation process and multi-stage reconstructions. Based on the exploration and development history of deep oil and gas, this paper points out China's take on it is at the “large-scale discovery stage during which significant achievements have been obtained in carbonate, clastic, and volcanic reservoirs. Nonetheless, there are still four challenges, namely: (1) complex hydrocarbon generation, reservoir evolution, and accumulation restriction on how to determine exploration orientation and targets; (2) long well drilling and completion period, as well as high well construction cost delay petroleum discovery and efficient development; (3) undeveloped logging technology for HPHT slim holes that cannot ensure accurate identification of hydrocarbon reservoir; and (4) effective development and large-scale utilization of unspecific recovery technique and equipment limit. Finally, by the comprehensive analysis, it is concluded that onshore deep oil and gas resources are mainly distributed in three areas of six basins in China. The areas have a vast exploration potential and have strategically successive resources. It is suggested that petroleum companies and universities, as well as research institutes, should work together to overcome difficulties in theory and practical technology for deep oil and gas exploration and development. Such partnership could develop fit-for-purpose theories and technical systems to support deep oil and gas development.
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Keywords: Deep oil & gas onshore; Oil & gas resources; Exploration and development; Current status; Prospect

1. Introduction

Deep oil and gas resources, as their name implies, refer to oil and gas resources that are generated and accumulated in deep sedimentary layers. Initially, they generally refer to oil and gas resources that are formed or enriched in the sedimentary layers below the “oil-generating window.” [1] However, the depths of oil-generating windows in different basins are quite different. Even in various areas of the same basin,

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oil-producing windows are greatly dissimilar. Therefore, there is no unified and strict international standard for the definition of "deep reservoir." Hence, different countries, industries, and even different institutes in the same industry have different definitions of "deep reservoir." At present, reservoirs buried below 4500 m are defined as a deep reservoir internationally. In the "Regulation of Petroleum Reserves Estimation" as issued by China National Commission for Mineral Reserves in 2005, reservoirs buried at 3500–4500 m are deemed as deep reservoirs. Meanwhile, reservoirs buried below 4500 m can be classified as ultra-deep reservoirs. In Chinese drilling engineering, the target layer located at 4500–6000 m is called a deep layer, whereas the target layer below 6000 m is called an ultra-deep layer [2–5]. In oil and gas exploration, it is difficult to distinguish "deep reservoirs" from "ultra-deep reservoirs." Thus, this paper generally refers to "deep" and "ultra-deep" reservoirs as deep reservoirs. Furthermore, deep oil and gas resources refer to the oil and gas in the reservoir with a depth of more than 3500 m in eastern basins and more than 4500 m in western basins.

In recent years, a series of major discoveries have been made. In addition, a number of large-scale reserves has been proven in the following areas: Keshen-Dabei area within the Kuche Depression and the Halahatang Sag in the Tabei Uplift of Tarim Basin; the Permian–Triassic platform margin beach and reefs in the northeastern area; the Sinian-Cambrian in the central uplift; the Middle Permian Qixia Formation-Maokou Formation in Sichuan Basin's western area; deep clastic rocks and deep buried hills in the Bohai Bay Basin; and deep volcanic rocks in the Songliao Basin and the Junggar Basin. Deep reservoirs have become important targets in discovering and increasing onshore oil and gas reserves in China.

This paper analyzes the current status, challenges, and prospects of deep oil and gas exploration and development. The study will also encompass hopes in order to continue the development of related theory, support engineering technology, as well as provide a reference in making decisions on exploration and development of deep oil and gas in our country.

2. Basic properties of deep oil and gas resources

2.1. More gas, less oil, and complex phases

Pang et al. [6] found gas accounting for 42%, oil for 7%, and oil-gas for 51% in 1477 deep reservoirs all over the world. In comparison to middle and shallow reservoirs, there is more gas than oil in deep reservoirs. According to the traditional kerogen genesis theory, two points cause the increase of natural gas in deep reservoirs: (1)as buried depth increases, formation temperature increases, kerogen is in highly-overmature stage, and kerogen-decomposing gas gradually dominates the resources; (2)liquid hydrocarbons generated in the middle and shallow reservoirs crack into natural gas at a high temperature and deep burial depth. New research indicates that many factors can influence the phase behavior of deep hydrocarbons. Geothermal gradient, burial depth, pressure (E.g., high pressure may inhibit the conversion of liquid oil to natural gas), and buried evolutionary history (progressive burying, early deep burying, and late uplifting, shallow early continuous burying and deep late quick burial) also affect hydrocarbon phase in addition to well-known source rock type [7]. Exploration practice also confirmed that large oil fields could be formed in deep reservoirs. For example, liquid hydrocarbons dominate the reservoir below 6000 m in the Rocket Mountain Basin and the North Caspian Basin. Black crude oil has been produced from the reservoirs deeper than 7000 m in the Tabei Uplift of the Tarim Basin; especially in the Jizhong Depression in the Bohai Bay Basin. Jixian Misty Mountain Formation's Well Niudong 1 at 5639 m produced natural gas and oil amounting to 56.3×10^4 m^3/d and oil of 642.9 m^3/d, respectively during the production test. In addition, deep buried high-temperature hill reservoirs in eastern China was declared to be found at the bottom of the hole (6027 m) at over 200 °C [8]. The discovery of deep oil and gas in the world has broken through the range of the oil-generating window (60–120 °C) and gas-generating window (0.6%–1.35%) as estimated by early kerogen theory. Accordingly, the phases of deep oil and gas are more complex, including liquid hydrocarbon, condensate oil, condensate gas, gaseous hydrocarbon, and oil-gas.

2.2. High temperature and pressure, as well as profoundly different basins or formations

Different regions in unlike basins have dissimilar geothermal gradients and temperatures at oil and gas reservoirs, but all tend to have higher temperature as the depth increases. Therefore, the temperature of deep reservoirs is generally higher—it may be well over 370 °C, and the temperature distribution is broader [9].

Most reservoirs are at high pressure in deeply buried reservoirs, except a few at low pressure. There are two kinds of pressure systems: (1) normal pressure system, where deep burial and high hydrostatic pressure result in high reservoir pressure; (2)abnormal pressure system, where the reservoir pressure is significantly higher than the hydrostatic pressure and the pressure coefficient is high. The formation of abnormally high pressure is related to the reservoir type, hydrocarbon accumulation type, evolution process, etc. Deep reservoirs at high temperature and pressure have varying temperature fields in specific basins in the main. There are often several pressure systems overlapping in deep reservoirs brought by complicated genesis and distribution rules. For example, in the Sichuan Basin, gas reservoirs in the Anyue gas field and the Cambrian Longwangmiao Formation are at abnormally high pressure (with a pressure coefficient of 1.5–2.2), while the Sinian Dengying Formation gas reservoirs below have a normal pressure coefficient (1.0–1.02). High temperature and pressure environment have significant impacts on hydrocarbon generation, hydrocarbon phase transformation, reservoir diagenesis, pore formation and evolution, hydrocarbon migration, as well as accumulation and preservation (Fig. 1).

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