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Original research paper

Status and prospects of exploration and exploitation key technologies of the deep petroleum resources in onshore China☆

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Abstract

In recent years, China's deep oil and gas exploration and exploitation have developed rapidly. Technological advancements have played an important role in the rapid exploration and highly efficient development. Aimed at the complex engineering geological environment of deep oil and gas in China, this paper has combined the four technological systems that have made significant progress, mainly including: (1) seismic imaging and reservoir prediction techniques for deep—burial complex structures, includign “2W1S” technique (wide-band, wide azimuth, and small bin), RTM (Reverse Time Migration), integrated modeling technology for complex structures and variable velocity mapping technique, improving structural interpretation accuracy, ensuring high precision ofimaging, and prediction for deep geological bodies; (2) deep speed raising and efficiency drilling technology series, which significantly improved the drilling speed, in turn reduced the drilling cost and drilling risk; (3) development of a deep high-temperature and high-pressure logging technology series, which provided a guarantee for the accurate identification of reservoir properties and fluid properties; (4) the efficient development technology for deep reservoirs, especially the development and maturity of the reconstruction volume technology, improve the production of single well and the benefit of deep oil and gas development. This paper further points out the improvement direction of the four major technology series of deep oil based on the analysis of the current development of the four major technological systems. Moreover, the development of applicability and economy for technical system is the key to realize high efficiency and low-cost exploration and development of deep oil and gas.

Keywords: Deep oil & gas; Exploration and exploitation technologies; Seismic; Logging; Drilling; Petroleum reservoir stimulation

1. Introduction

The increase in drilling depth is a result of technological advances. Well Bertha Rogers 1, made in the US in 1974, was drilled to the depth of 9583 m. Well Kola SG-3, drilled on the Kola Peninsula in Russia, reached 12260 m. Chayvo Well Z-44, the deepest oil well in the world by far, was drilled at a

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depth of 12376 m on the Sakhalin Island in Russia in 2012 [1]. As per the summary of statistics made by Krayushkin [2], there were more than 1000 oil and gas fields exploited at the depth interval between 4500 m and 8100 m. The first recoverable oil reserves accounted for 7% of global oil reserves and gas reserves accounted for 25% of global gas reserves. In the US, Italy, and Mexico, the proven oil and gas reserves with a high degree of deep-zone prospecting have accounted for 31% and 47% of the total oil and gas reserves, respectively. Pang [3] stated in 2015 that 42%, 51%, and 7% of 1477 discovered deep reservoirs around the world were gas reservoirs, oil and gas reservoirs, and oil reservoirs, respectively. Deep recoverable oil reserves were 105×10^8 t, accounting for 4.45% of the total recoverable oil reserves. The proven recoverable gas reserves were 70×10^8 t of oil equivalent, accounting for 4.71% of the total recoverable gas reserves. In China, deep reservoirs with considerable reserves have been discovered recently in: the Keshen-Dabei prospects in the Kuqa Depression, Tarim Basin; Halahatang prospect in the North Tarim Uplift; Permian−Triassic platform-margin reefs and banks in the northeastern Sichuan Basin; Sinian-Cambrian Systems in the central Sichuan paleohigh; Qixia-Maokou Formations in the Middle Permian Series, western Sichuan Basin; deep clastic rocks and deep buried hills in the Bohai Bay Basin; and deep volcanic rocks in the Songliao and Junggar basins. Deep hydrocarbons have become an essential component in onshore petroleum discoveries and reserves increase [4−15].

The breakthroughs in deep hydrocarbon exploration were brought about by theoretical and technological advances, which in turn promoted deep hydrocarbon exploration and exploitation techniques. For example, Ordovician fractured-vuggy oil reservoirs in Halahatang in the northern Tarim Basin were mostly discovered through seismic sculpting and prediction techniques. The methodologies adopted were further developed into a portfolio of techniques in exploration and exploitation activities. The said methods then played a crucial role in the exploration and development of additional karstic fractured-vuggy reservoirs in the central and northern Tarim Basin [16−18]. The improved seismic imaging of Permian−Triassic reefs and banks in the Sichuan Basin gave rise to the discovery of lithologic gas reservoirs on both sides of the Kaijiang-Liangping trough and deep gas reservoirs in Puguang and Longang prospects. Further development of seismic techniques for reef-bank prediction by gas exploration and exploitation in Puguang and Longang promoted the discovery of the Yuanba gas field as well as reserves and production increase. These techniques, having been successfully applied to seismic prediction of Sinian Dengying microbial and Cambrian Longwangmiao grain-bank dolomite reservoirs in Sichuan Basin, will play (or played) an essential role in petroleum exploration and production in the Anyue Gas Field [19−21].

Deep hydrocarbon reservoirs in China usually reside in the infrastructures in superposed basins. Boreholes have to penetrate different formation systems to reach deep beds of interest. The said phenomenon leads to three complexities of engineering geology, namely: (1) coexisting unconsolidated formations, salt and gypsum formations, as well as fractured-vuggy formations; (2) coexisting multiple pressure systems; and (3) high-temperature, high-pressure, and high-sulfur content in gas reservoirs. Thus, there are five points in deep hydrocarbon prospecting and production in China. The five points are: (1) locating prospects, (2) pinpointing targets, (3) drilling targets, (4) confirming targets, and (5) petroleum recovery with high efficiency. All except for the first point, are related to engineering including seismic, well drilling, well completion, well logging, and recovery techniques. Strengthened deep hydrocarbon exploration, exploitation, and specialized research at country and company levels in the recent years have accelerated the development of techniques related to deep hydrocarbon exploration and exploitation. This paper deals with current vital techniques, challenges, and prospects of deep hydrocarbon exploration and exploitation in China.

2. Existing key techniques

A portfolio of comprehensive techniques is necessary for deep oil and gas exploration and exploitation. The portfolio can aid high efficiency given the challenges of seismic prediction of massive deep hydrocarbon after multi-phase accumulation and alteration, development models in the context of high temperature, high-pressure and high-sulfur content, as well as harsh geologic environments with high-temperature, high-pressure, high-salinity, and high-grinding. Thanks to the rapid advancement of deep exploration and exploitation in the recent years, the four technological systems have now been tentatively established.

2.1. Seismic imaging of deep−burial complex structures and deep reservoir prediction

Poor seismic data quality in deep zones may be attributed to high-frequency attenuation and the existence of high-velocity layers in shallow zones. The challenges include: (1) varied surface and near-surface conditions, poor shooting and receiving conditions, as well as heavy noises; (2) amplitude-preserved imaging of weak reflections from deep zones; (3) seismic wavefields made extremely complicated by highly-fractured deep structures and steeply dipping formations; (4) low signal to noise ratio, low imaging accuracy, and low confidence of trap delineation; and (5) low credibility of reservoir characterization due to small contrasts between reservoirs and non-reservoirs [22,23].

A suite of techniques, including digital seismic acquisition, migration, complex structure modeling, and velocity-varied mapping was established for deep−burial complex structure imaging and reservoir prediction so as to address the issues stated above.

I Digital seismic acquisition

An ideal seismic acquisition system is target oriented and dependent on surface and geologic conditions. A digital