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RESEARCH PAPER

Formation mechanism, geological characteristics and development strategy of nonmarine shale oil in China

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Abstract: As an important type of "conventional–unconventional orderly accumulation", shale oil is mature oil stored in organic-rich shales with nano-scale pores. This paper analyzes and summarizes elementary petroleum geological issues concerning continental shale oil in China, including sedimentary environment, reservoir space, geochemical features and accumulation mechanism. Mainly deposited in semi-deep to deep lake environment, shale rich in organic matter usually coexists with other lithologies in laminated texture, and micron to nano-scale pores and microfractures serve as primary reservoir space. Favorable shale mainly has type Ⅰ and $Ⅱ_A$ kerogens with a R_o of 0.7%–2.0%, *TOC* more than 2.0%, and effective thickness of over 10 m. The evolution of shale pores and retained accumulation pattern of shale oil are figured out. Reservoir space, brittleness, viscosity, pressure, retained quantity are key parameters in the "core" area evaluation of shale oil. Continuously accumulated in the center of lake basins, continental shale oil resources in China are about 30×10^8–60×10^8 t by preliminary prediction. Volume fracturing in horizontal wells, reformation of natural fractures, and man-made reservoir by injecting coarse grains are some of the key technologies for shale oil production. A three step development road for shale oil is put forward, speeding up study on "shale oil prospective area", stepping up selection of "core areas", and expanding "test areas". By learning from marine shale breakthroughs in North America, continental shale oil industrialization is likely to kick off in China.

Key words: shale oil; shale gas; shale system; nano-scale pore-throat; unconventional hydrocarbon; conventional-unconventional orderly accumulation

Introduction

The worldwide petroleum industry is now making a historic leap from conventional oil and gas to unconventional oil and gas. Unconventional oil and gas is mainly composed of hydrocarbon accumulation in shale plays, which includes tight oil and tight gas as well as shale oil and shale gas. Tight oil and gas refers to petroleum and natural gas accumulated in such reservoir rocks as tight sandstone or limestone after short-distance migration. Shale oil and gas refers to petroleum and natural gas gathered in black organic-rich shale basically without migration. At present, shale gas is becoming popular in global unconventional gas exploration and development [1–5] and relevant research on shale oil has been done. In the light of comprehensive investigations of the latest advances in tight oil & gas and shale oil & gas exploration, development and research [1, 5–10], this paper summarizes basic concepts and features of shale oil from research findings of shale oil in some terrestrial lake basins in China including the Mesozoic Yanchang Formation in the Ordos Basin, and elucidates some fundamental issues in petroleum geology concerning shale oil accumulation, e.g. sedimentary environment, geochemical features, reservoir space and accumulation mechanisms. Finally, this paper will forecast the shale oil resource potential in China, and put forward some criteria for evaluation of shale oil "core area" and the concept of "three-step development".

1 Background

The global oil industry has been breaking the maximum temperature limit of hydrocarbon generation, the minimum pore-throat limit of hydrocarbon preservation and the maximum depth limit of hydrocarbon accumulation time and time again, leading to great changes of hydrocarbon development extending from land to deep water, from shallow and middle zones to deep and ultra-deep zones, and from conventional oil and gas to unconventional oil and gas. Three new domains with strategic significance in the petroleum industry will be: plays in ultra-deep waters below the depth of over 3 000 m,

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terrestrial strata below the depth of over 6 000 m, and new tight reservoir types with pore size less than 1 000 nm.

Nowadays, unconventional oil and gas revolution represented by shale gas is raising a petroleum science and technology revolution, which has three features, i.e. subversion of traditional theories, technical breakthroughs and factory-like production. The fact that the exploration of unconventional oil and gas shifts from searching for traps to searching for extensive reservoirs overthrows the traditional theory of oil and gas accumulation in traps; the transformation from conventional development with vertical wells to large-scale fracturing and horizontal well technology breaks the traditional vertical well development pattern; the transformation from single well to "factory-like" multi-wells also breaks the traditional single well development mode.

Petroleum industry will undergo three stages, i.e. conventional oil and gas, conventional and unconventional oil and gas with an equal amount of importance, and unconventional oil and gas development, forming a complete lifespan of the industry. The lifespan of the petroleum industry is anticipated to be about 300 a; since the birth of the modern petroleum industry in 1859, more than 150 years have passed. In 1934, the 'trap theory' proposed by Mccoloagh is a landmark of conventional petroleum geology and was applied to the exploration and development of conventional resources. In 1995 Schmoker et al. presented the concept of continuous hydrocarbon accumulation, which is a milestone in the unconventional accumulation theory and has laid a scientific foundation for the effective exploitation and utilization of unconventional resources [6–10]. Due to constant innovations of petroleum theories, technologies, approaches and subversion of the peak theory proposed by Hubbert in 1956, global peak oil yield may be postponed from the 1960s to the 2030s or 2040s and the lifespan of the petroleum industry may exceed 300 a [6–10].

Unconventional oil and gas refers to those continuously or quasi-continuously distributed hydrocarbon resources which cannot be recovered with traditional technologies to obtain desired volume. Thus permeability or fluid mobility of the reservoir has to be improved via new technology in order to make the resource endowment economically recoverable. The essential differences between conventional and unconventional accumulation lie in two aspects, one is whether hydrocarbon distribution is dominantly controlled by traps or not and the other is whether or not individual wells have natural commercial productivity. Unconventional accumulation has two key features: (1) extensive ranges of hydrocarbon distribution with no clear trap boundaries; (2) absence of stable natural commercial productivity and a distinct Darcy flow.

"Orderly accumulation" of conventional and unconventional hydrocarbon resources refers to a system in which conventional and unconventional oil and gas are continuously charged and orderly distributed in hydrocarbon-rich basins or depressions; the conventional oil & gas and unconventional oil & gas form a symbiotic co-existence. Under these rules, spatial hydrocarbon distribution of different types may be predicted; research on and exploration of conventional and unconventional oil and gas should be carried out simultaneously through large-scale well fields because discoveries of the conventional usually indicate the possible existence of the unconventional in the source direction, and discoveries of the unconventional may also indicate associated conventional resources in peripheral space. By doing so, exploitation can be carried out more efficiently. The ratio of unconventional to conventional is 8:2. Hydrocarbon reservoirs of different types are determined by reservoir pore-throat sizes and would occur in orderly distribution. In the lateral direction, conventional structural reservoirs or lithologic-stratigraphic reservoirs may generally be distributed at basin margins or slopes and unconventional tight oil and gas or shale oil and gas may concentrate in depressions or depocenters; in a vertical direction, distal conventional reservoirs, proximal tight oil and gas and shale oil and gas within source areas are distributed in a descending order. In the past, the approach used in surveying for oil and gas varied with different stages: exploration at the early and middle stage concentrated on conventional hydrocarbon resources, aiming at finding large-scale structural reservoirs based on the "source control theory" and structural and lithologic-stratigraphic reservoir groups based on theories of "complex hydrocarbon accumulation" or "large hydrocarbon province"; the middle and later stages are unconventional hydrocarbon resources-oriented—proximal tight oil and gas as well as shale oil and gas within source areas based on the theory of "continuous hydrocarbon accumulation".

Fractured shale oil and gas has now been discovered in different basins around the world like Appalachia, the Gulf of Mexico, West Siberia and Songliao Basin, and it has become a common understanding that oil and gas may be yielded from special mud shale fractures [6]. As for the issue of profitable accumulation and economic production of shale oil in matrix, experts and the industrialists maintain a negative and pessimistic attitude and up to now, no breakthrough has been reported on economically recoverable shale oil in matrix. The organic-rich black shale has generally been taken as source rock to generate oil or as seal rock to prevent oil and gas from further migration instead of reservoir rock, therefore it has never been paid enough attention to in exploration and development. But the abundant shows of oil and gas in organic-rich black shale drilled by many wells have demonstrated the fact that shale oil resources exist in organic-rich shale.

2 Essential features of shale oil

2.1 Shale oil defined

Shale oil refers to the petroleum preserved in those nano-scale pores in organic-rich shale and is short for mature-organic shale oil. In this system, shales act not only as source rock but also as reservoir rock. Shale oil, generally light oil with low viscosity, occurs in adsorption and free state in nano-scale pore-throats and fractures along lamellar bed-