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RESEARCH PAPER

Breakthrough and significance of unconventional oil and gas to classical petroleum geology theory

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Abstract: Great changes of the global energy industry have been caused by the rapid development of unconventional oil and gas. It is necessary to deeply consider the profound influence of the unconventional oil and gas revolution on the classical petroleum geology theory and to review geological conception of oil and gas accumulation elements and theoretic framework of petroleum system, giving the petroleum geology a new academic connotation. The author summarizes the significant progresses of global unconventional oil and gas exploration and development, and points out that the unconventional oil and gas revolution not only has a significant economic significance of oil and gas resource increment, but also brings great innovation to the theory of petroleum geology, thus having important scientific significances. This paper summarizes the core contents of four aspects of hydrocarbon generation, reservoir, distribution and development in classical petroleum geology, and comprehensively reviews the five important nodes in the developmental history of petroleum geology, which include anticline and trap theory, hydrocarbon generation from organic matter and petroleum system theory, continental petroleum geology, marine deepwater petroleum geology, continuous hydrocarbon accumulation and unconventional petroleum geology theory. Unconventional oil and gas has made a great breakthrough to classical petroleum geology on the basic theoretical concepts such as trap, reservoir, caprock, resource distribution, and enrichment, thereby promoting the basic research on petroleum geology to transform into the whole process of hydrocarbon generation, whole type of reservoir, and whole genetic mechanism, deepening unconventional petroleum geology theory, promoting the development and reconstruction of petroleum geology system, representing great significances to the strategic development from conventional to unconventional oil and gas in China or even in the world.

Key words: petroleum geology; unconventional petroleum geology theory; continuous hydrocarbon accumulation; tight oil and tight gas; shale oil and shale gas; oil and gas production

Introduction

Rapid development of unconventional oil and gas in the past decade has given rise to all-around changes in the supply-demand structure, recovery method, and technical innovation in the petroleum industry[1–8]. It is necessary to deeply consider the profound influence of unconventional discoveries on classical petroleum geology and review hydrocarbon accumulation elements and the theoretical framework of petroleum system. The connotation of petroleum geology enriched with some new ideas will facilitate the development of basic theories and integrated evaluation of conventional and unconventional resources in a petroliferous basin to improve overall exploration and development deployment.

1. Major advances in unconventional petroleum exploration and development

Unconventional oil and gas have been playing an increasingly important role in global petroleum production, which has been demonstrated by the commercial production of oil sands, tight gas and coalbed methane (CBM) and rapid increase of shale gas and tight oil production caused by the U.S. shale gas revolution[1–8].

1.1. Overview of unconventional petroleum exploration and development

1.1.1. Global unconventional oil production

Unconventional oil resources include oil shale, oil sands, heavy oil and tight oil (including shale oil). Global unconventional oil production was 4.8×10^8 t in 2015, accounting for 11% of total oil production[9]. Oil shale yield was limited due to the issues of production cost and environmental pollution. Canada and Venezuela are the major two countries for oil sand and heavy oil production. Commercial production of tight oil was first realized in the US.

More than 70% of global oil sand resources accumulate in the Western Canada Sedimentary Basin. Oil sand bitumen of

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8.6×10^4 t was recovered at the land surface in 1968 and consequently new proved oil reserves were increased by 10×10^8 t[10]. Bitumen output increased from 13×10^4 t[10] by thermal recovery in 1982 to 3893×10^4 t in 2000 to 1.4×10^8 t[10] in 2015. It is anticipated by IHS that oil sand yield will be 40×10^4 t/d[9] in 2020 due to the impact of low oil prices.

The US is a leader in commercial tight oil production around the world. Tight oil output was 1800×10^4 t[9] in 2000. Thanks to the application of horizontal well multi-stage fracturing, a technique which was commonly used in shale gas production, in 2008, the production increased to 2.1×10^8 t[9] in 2015, 7.2 times more than that in 2008. Conventional oil production declined from the peak of 5.3×10^8 t in 1970 to 3.0×10^8 t[11] in 2008. But successful tight oil production gave birth to the second oil peak of 5.7×10^8 t[11] in 2015 and sustained increase in oil yield.

1.1.2. Global unconventional gas production

Unconventional gas resources include tight gas, CBM, shale gas and gas hydrate. Global unconventional gas production was 8227×10^8 m^3 in 2015, accounting for 23% of total gas production.

The first breakthrough in the commercial production of unconventional gases is tight gas production, which has been stabilized now. The Cauthage field in the US yielded daily gas of 340×10^4 m^3 in 1955 after acid fracturing and became the largest gas field in the US in 1976. The US tight gas production exceeded 600×10^8 m^3 in 1990 and $1\ 000\times10^8$ m^3 in 1998 and climbed to a maximum of $1\ 300\times10^8$ m^3 in 2011; after that the production was stabilized and came to $1\ 200\times10^8$ m^3 in 2015[9]. Commercial tight gas production was also realized in Canada and China. Global tight gas production reached $2\ 450\times10^8$ m^3 in 2015.

As for unconventional accumulations in self-sourced reservoirs, CBM is the first one with commercial production. Natural gas recovery from high-pressure coal beds began in the San Juan Basin, the US, in the 1950s. In 1980, the United States enacted the Crude Oil Windfall Profit Tax Act, which greatly promoted CBM production. In 1992, the US CBM yield arrived at 260×10^8 m^3[12]. Due to the application of open-hole cavern completion and multilateral well drilling, the US CBM yield reached a peak of 557×10^8 m^3[12] in 2008 and 280×10^8 m^3[12] in 2015. Commercial CBM production was also realized in Canada, Australia and China. Global CBM production reached $1\ 000\times10^8$ m^3[12] in 2015.

Commercial shale gas production is of revolutionary significance. In 1821 the first shale gas well was drilled in the US onshore. The first shale gas field, Big Sandy, was discovered in the US in 1914. In 1981, George Mitchell, honored as the father of shale gas, and his engineers developed the technique of hydraulic fracturing to exploit the Barnett Shale with commercial yield[9]. Due to mass production of Antrim and Barnett shale gases, gross output in 2000 reached 230×10^8 m^3. The proved technique of horizontal well multi-stage fracturing was widely used in 2005 to stimulate shale gas production. Thanks to the exploitation of some large shale gas fields including Marcellus, the US shale gas yield reached 4250×10^8 m^3[9] in 2015. Commercial shale gas production was also realized in Canada, China and Brazil. Global shale gas production reached 4693×10^8 m^3[9] in 2015.

1.2. Economic significance of unconventional oil and gas production

In view of abundant unconventional resources and low degree of conventional reserve recovery which have been demonstrated by exploration and development activities and global petroleum resources assessment, it is anticipated that the petroleum industry will experience three stages, i.e. conventional petroleum production, co-production of conventional and unconventional resources, and unconventional petroleum production[4–8]. Hubbert's peak oil theory presented in 1956 has been overthrown because of consistently rising estimations of peak oil and gas production due to the discoveries of unconventional resources. The life span of the petroleum industry may exceed 300 years[4–8] for the smooth transition to a new energy era. It is anticipated that the petroleum industry, instead of being terminated due to resources exhaustion, will be progressively replaced by a new industry to produce environment-friendly renewable energy.

Global unconventional oil resources are equivalent to conventional oil resources, while unconventional gas resources are far more than conventional gas resources. Recoverable unconventional oil resources are estimated to be 6200×10^8 t, which include heavy oil of 1079×10^8 t, oil sands of 1067×10^8 t, oil-shale oil of 1051×10^8 t, and tight oil of 473×10^8 t (Fig. 1a). Global recoverable unconventional gas resources are estimated to be close to 4000×10^{12} m^3, which include tight gas of 210×10^{12} m^3, CBM of 256×10^{12} m^3, shale gas of 456×10^{12} m^3, and gas hydrate of 3000×10^{12} m^3 (Fig. 1b)[9–12].

Conventional oil and gas with a production history of more than a century have motivated industrial development. Cumulative conventional oil production is estimated to be 1732×10^8 t with the degree of reserve recovery of 35%. Cumulative conventional gas production is estimated to be 79×10^{12} m^3 with the degree of reserve recovery of 17%. This means remaining resources are still sufficient to sustain long-period production and supply. As an emerging type of resources, the potential production of unconventional oil and gas are large in spite of the negligible output nowadays. It is anticipated by EIA that global unconventional gas yield will increase from 8227×10^8 m^3 in 2015 to 2.48×10^{12} m^3 in 2040[9], accounting for 42% of total gas production. Shale gas, tight gas and coalbed methane yields will increase to 1.7×10^{12} m^3, 0.46×10^{12} m^3 and 0.32×10^{12} m^3, respectively[9], accounting for 29%, 8% and 5% respectively of total gas production. Global unconventional oil yield is anticipated to increase from 4.8×10^8 t in 2015 to above 10×10^8 t in 2040, accounting for 20% of total oil production. Tight oil and oil sand bitumen yields will