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REVIEW PAPER – EXPLORATION ENGINEERING

The geological characteristics and exploration of continental tight oil: an investigation in China

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Abstract

Tight oil is an important and potential reservoir in future China. Drawn from the successful exploration of tight oil in North America, tight oil exploration is now in progress in China. In this paper, we surveyed the tight oil exploration status and challenges, as well as the tight reservoir properties in China, including source rocks, lithology, physical properties and pressure coefficient. The process of pilot test and key technologies are analyzed, while it is still urgent to improve tight oil study and the production mode. We concluded that there are 4 aspects, which are geological features, energy supplement for formation, engineering and technical management innovation, should be improved, and national policy support for tight oil is another key point for successful exploration.

Keywords Tight oil reservoirs · Reservoir properties · Nano-technology · Hydraulic fracturing

Introduction

According to the China's petroleum industry standard "Tight Oil Geological Evaluation Method" of 2013, tight oil in China refers to the oil in the tight sandstone, tight carbonate and other reservoir for which matrix permeability under overburden pressure is less than or equal to $0.2\times10^{-3}\mu m^2$, the air permeability is less than or equal to $2\times10^{-3}\mu m^2$. Natural productive capacity of tight oil is lower than the industrial oil flow. However, the tight oil can be obtained with certain economic and technical conditions such as horizontal well and hydraulic fracturing. As the conventional oil and gas resources were more extensively developed, the tight oil formations became an important substitutable resource for oil exploration.

The mechanisms of hydrocarbon accumulation, microscopic pore structure, seepage mechanics of tight oil reservoir have been studied intensively abroad, lot of laboratories carried out displacement experiments with tight core, the results showed that miscible displacement of CO_2 puff and huff could get relatively higher recovery efficiency. In addition, the technology of tight oil exploration such as 3D seismic interpretation, massive hydraulic fracturing, jet pump have been applied widely on tight reservoirs. With the technical supports, commercial exploration of tight oil has come true in North America (Tong 2007). In 2012, the tight oil production reached 97 million tons in the United States, about 22% of total oil production. The United States stopped the import of light crude in 2013, since the increasement of tight oil production exceeded prediction. The IEA (International Energy Agency of USA) forecasted that the tight oil production will reach 150 million tons, which is about one-third of total production, this will cause the USA shift from energy importer to energy exporter. The global production of tight oil will reach 250 million tons. The successful cases of tight oil exploration in the United States have a significant impact on the world energy pattern (Lu 2011; Zhao 2000; Zhang 2008; Lin et al.. 2008).

With the rapid development of economy, the energy consumption grows rapidly in China. As the world's largest energy consumer, the total oil consumption in China exceeded the United States in 2010, which is 10 years earlier than the prediction of institution in China. As shown in Fig. 1, with the progress of the urbanization, the oil consumption growth will last for a long time. Oil production in our country is about

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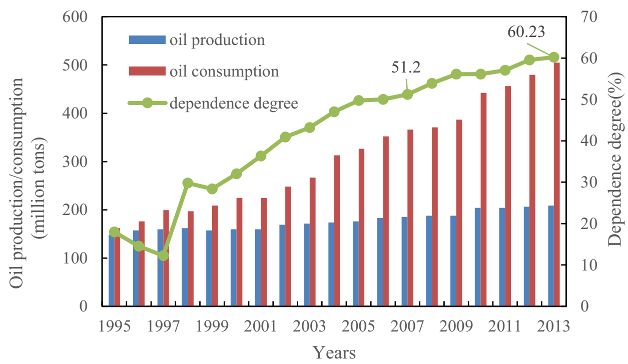

Fig. 1 The oil production/consumption and dependence degree of China (Source from: CNPC Economics $ Technology Research Institute "Domestic and international oil and gas industry report")

200 million tons, which has entered a relatively stable period since 2004. The average annual growth of production is about 2.18%. However, the average consumption growth is 6.35%, which lead the oil dependency degree higher and higher. The oil production of 2013 was 210 million tons, while the consumption was 490 million tons, leading to an oil import of 280 million tons. The oil dependence degree has broken through 60% since then (Zou et al.. 2013). Therefore, the exploration of tight oil, including the development strategy, related geological theory and engineering technology, are of great significance.

The petroleum accumulation mechanism of tight oil has been studied thoroughly based on the core observation, thin slice identification, X-ray diffraction analysis, TOC test and rock pyrolysis test of source rock samples (Yao et al. 2015; Ren et al. 2011; Qiu et al. 2016; Shi et al. 2015; Liu 2015; Zou et al. 2012). The electron microscope scan experiment of tight oil microscopic pore structure was carried out by the Beijing Research Institute of Petroleum Exploration and Development (RIPED) and China University of Geosciences (Guo et al. 2009). The seismic prediction for 'dessert', well logging evaluation, fast drilling and hydraulic fracturing transformation were also carried out. Several pilot tests were built, the integrated approach of "fracturing-exploration" for tight oil horizontal well were formed initially.

This paper aims to show an overall status of the tight oil exploration in China, as well as the challenges in current oil price. This study can provide a better understanding of the tight oil in China including geological characteristics, exploration technique and the pilot progress.

Table 1 The characteristic of source rocks of tight oil in China

Types	TOC (%)	Ro (%)	Potential hydrocarbon generation amount (mg/g)
High abundance shale	2.0–13.0	0.5–2.0	12.0–65.0
High abundance sedimentary tuff and malm	1.0–15.0	0.7–1.2	5.0-75.3
Low abundance shale	0.5–1.5	0.6–1.8	2.0–5

Reservoir characteristics of tight oil resources in China

The tight oil resources of our main basin in China is about 10 billion tons, preliminary evaluated by Beijing RIPED. From the national onshore oil exploration situation, the additional reserves are mainly low grade resource, the main objects in petroleum exploration and development are low and ultra-low permeability reservoirs (Zhao 2012; Li et al. 2007).

In contrast with the tight oil of marine sedimentary environment in North America, there are big differences between deposition, hydrocarbon source rocks, reservoir characteristics and fluid characteristics of tight oil reservoir in China. Tight oil reservoirs in China are mainly in fault-depression and down-warped lake basin environment with high heterogeneity, which are the results of deep and semi-deep lacustrine environments. The tight oil reservoirs in China are composed by dark mudstone and shale, distributed widely in lake-basin center with large scale, range from several thousand to ten thousands of square kilometers. The layers consistent with good quality hydrocarbon source rocks characterized by TOC (Total Organic Carbon) > 2%, and moderate thermal evolution with the Ro (Vitrinite Reflectance) range from 0.6 to 1.5%. The major characteristics of tight oil in China are introduced from the four following aspects: hydrocarbon source rocks, lithology, fluid properties and pressure coefficient (Hu et al. 2018, Zhu et al. 2016).

The hydrocarbon source rocks

The thickness of North American marine hydrocarbon source rocks is usually several tens of meters, with TOC values of 2–20%, and Ro values of 0.6–1.7% (Hu et al. 2018). There are many types of source rocks characterized by high organic material content, all the three types of hydrocarbon source rocks can form tight oil reservoirs with a maximum TOC value of 15% (Li et al. 2007). The characteristics of source rocks are shown in Table 1.

Table 2 The characteristics of tight sandstone reservoirs

Type	Layers	Main lithology
Sandstone	Ordos Yanchang formation $Chang6_3$	Massive sandstone
	Songliao basin Fuyu layer	Siltstone, pelitic siltstone
	Ordos Yanchang formation $Chang8_1$	Mid-fine sandstones
	Ordos Yanchang formation Chang7	Silt-finestone
	Songliao basin Qingshankou group	Siltstone, marlstone
	Bohai Bay Cangdongkong	Silt-finestone, dolomite
	Qaidam basin southwestern	Silt-finestone

The lithology

There are three types of tight oil reservoirs in China, which are sandstone, carbonates and dolomitic. The effective reservoirs are small in scale and with poor properties, most widely distributed in Sichuan basin. The scales and properties have great differences between various types, the sandstone type developed better, which is widely distributed with better reservoir properties. The characteristics of tight sandstone, carbonatite and dolomitic reservoirs are shown in Tables 2 and 3.

Fluid properties

Due to the various reservoirs and hydrocarbon generation, saturation and fluid properties are of huge differences in various tight oil reservoirs in China. Ordos area is sandstone reservoir, Qaidam and Sichuan area are carbonatite reservoir with relatively low level of oil saturation. The fluid physical properties of different tight oil reservoir, are shown in Table 4.

Pressure coefficient

The pressure coefficient of tight oil reservoir of China is in the range of 0.7–1.6, which is lower compared with 1.35–1.8 of North America basin. The low pressure coefficient leads to an insufficient energy supply. It is hard to get stable production by depletion development. The differences of tight oil between China and abroad are shown in Table 5. The initial production of fractured well in the test area was high, while with a quick production decline.

Table 4 Fluid physical properties of different tight oil reservoirs

Basin	Oil saturation (%)	crude oil density (g/cm^3)
Ordos	80–90	0.80–0.88
Junggar	70–95	0.87–0.92
Sichuan	52–65	0.76–0.87
Songliao	40–50	0.78–0.87
Bohai bay	60–70	0.78–0.92
Qaidam	50–65	0.87
Santanghu	66–92	0.75–0.85

Table 5 Table of comparison on pressure coefficient of tight oil in major basins home and abroad

Type	Basin	Pressure coefficient
North America	Williston	1.35–1.58
China	Ordos	0.75–0.85
	Junggar	1.1–1.6
	Songliao	0.97–1.06
	Qaidam	1.25–1.3
	Santanghu	0.7–0.9

Exploration of tight oil in China

The preliminary practices showed that the exploration of tight oil in China is realistic. Tight oil resources are rich in our country. In recent years, an integrated development mode called factory-like operation was formed with

Table 3 The characteristics of tight carbonate and dolomitic reservoirs

Type	Layers	Main lithology
Carbonate	Sichuan basin Jurassic Da anzhai	Shell limestone
	Qaidam basinWest E32	Algal limestone, pelsparite
Dolomitic	Junggar jimusar Lucaogou group	Siltstone, detrital dolomite
	Santanghu basin Lucaogou group	Limestone, dolomite
	Bohai bay Shulu depression	Marlstone
	Santanghu basin Tiaohu group	Sediment-tuff
	Bohai bay Qikousha1 section	Dolomite, sandy dolomite
	Bohai Bay Liaohe basin west depression	Mud-crystal dolomite

re-fracturing, horizontal well drilling and massive volume fracturing (Jia et al. 2012; Du et al. 2014).

Field test

As a whole, the exploration of tight oil in China is in the stage of field test, which is going well. Three tight oil fields have been found in Ordos, Songliao and Junggar basins, other six prospective fields were found in Qaida, Jurassic, Sichuan et al. The exploration mode of each blocks is depletion-driven of horizontal well with hydraulic fracturing. The progress of pilot tests are shown in Table 6.

Progress of key technologies

Seismic Technology

Three key technologies applied innovatively in seismic technology to confirm the distribution of desserts, the coincidence rate of reservoir prediction reached more than 80%.

1. The sensitive physical parameters analysis was established, lay the foundation for reservoir prediction by creating the parameter plates of rock lithology, physical property and brittleness.
2. The reservoir thickness, porosity and brittleness can be predicted by vertical and horizontal wave impedance intersection analysis, which are realized by the application of pre-stack elastic-wave inversion and multi-parameter intersection analysis technology.
3. Multiple attribute fracture prediction technology can effectively identify favorable fracture development zone of reservoir (Dong 2004; Huang et al. 2016). The Daqing oilfield used seismic technology during fracturing operation to monitor the process of fracture. The seismic results show that geometric size of the fracture is extended stepwise. When the length of the fracture reaches a certain extent, the fracture is hardly spread forward. It will also be useless to add propping agent, while reaching the required flow conductivity of the reservoir by sand added.

Well logging technology

Seven properties of evaluation was carried out to provide the basis for horizontal well drilling, layer selection, well path design and fractures design. The specific technologies in application are shown in Table 7. The application of logging technology realize the fine identification of

Table 6 Pilot tests progress in China

Blocks	Exploration status	Geological characteristics	Production feature
Bakken	Commercial production,13,000 wells drilled, 12,000 still producing (including shale and tight oil)	Marine sediment with porosity 5–12%, permeability 0.5–10μm^2 and oil saturation 68%	Rapid decline
Ordos basin	Pilot test	Low pressure coefficient(0.75–0.85)	Recovery < 7%
Songliao basin	Multiple well group test	Oil saturation is low	Produce water in the initial stage of production
Jungar basin	Single well group test	High crude oil density(0.87–0.92 g/cm^3) and high viscosity(39.2–500 mPa.s) with poor fluidity	
Sichuan basin	Single well group test	Extremely low porosity(< 4%) and less effective use of reservoir	

Table 7 Table of logging technologies

Properties	Suitable logging technologies
Lithology	Elementary capture spectroscopy (ECS), electricity imaging logging
Physical property	Nuclear magnetic resonance (NMR), micro-resistivity imager logging
Oil potential	Dielectric microscope scanning, NMR logging
Electric property	Resistivity/density logging
Brittle	High precision array/scanning acoustic logging
Hydrocarbon source rock characteristics	Natural gamma ray spectral logging, NMR/density logging
Crustal stress	Electrical imaging technology, array/scanning acoustic logging

lithology, physical property of reservoirs and hydrocarbon layers identification.

Drilling and perforation technology

Drilling technology research advances drilling safely and quickly, which increased the drilling efficiency. The rate of reservoir drilling, drilling cycle and penetration rate were improved. The tight oil of continental deposits environment in China are characterized by poor lateral stability and small longitudinal thickness. Chang 7 layers in Ordos basin is of high heterogeneity, with thin layer body thickness and fast lithologic changing, which limit the design of horizontal well. Fuyang layer in Daqing oilfield is characterized with thin interbed, the thickness of single sand body is only 3–5 m.

It is reported that the penetration rate increased by 38% and drilling cycle reduced by 40% in Ordos basin Chang 7 horizontal well (Su 1996; Wang et al. 2015). Daqing oilfield studied the optimal method for number and distribution of perforation, which ensures that each cluster of fractures extends steadily. A plate is built through the relationship between single-hole flow and borehole friction, based on current limiting method. The plate suggested that the single-hole flow rate should be above 0.45 m^3/min, and should be above 0.5 m^3/min for the bigger hole size to ensure enough perforation friction. Based on the fracture model, the optimal perforation distribution is got by simulation of the fracture initiation and extension for different combination patterns.

Fracturing technology

In the aspect of hydraulic fracturing optimization design, fractured interval optimized, fracture reorientation and crack scheme optimization were applied to reduce inefficient fracturing, and improve the transformation rate for dessert and the reservoir producing ratio. The polyhydric alcohol and low concentrations of guar gum were applied in fracturing fluid system. The core damage rate reduced by 18–20% and the cost decreased by 20–35% (Cao et al. 2010). The double-sealing and single-stick subsection fracturing, packer slip subsection fracturing, hydraulic sandblasting subsection fracturing and open hole packer slip sets of subsection fracturing were applied to realize subsection fracturing of large volume. Daqing oilfield established diagnosis and control technology, based on microseismic monitoring and hydraulic fracture operating curve. The adjustment of sand process and Stimulate Reservoir Volume (SRV) are done in real time, which realized the risk controlling as the same time.

Nanotechnology

As the discovery of nanopore throat in oil and gas reservoir (see Fig. 2), the concept of nano petroleum was proposed and the nanotechnologies were put into application (Zou et al. 2010, 2012). Nanotechnology refers to manufacturing stuff with single molecular or atom with the structure dimension range 1–100 nm (Zhang et al. 2000). Nano characterization technology has played an important role in the analysis of the mineral composition, micro pore structure and rock physical properties of unconventional reservoirs (Liu et al. 2016). Nano materials, especially nano particles have already used to improve the diffusion (Ayatollahi 2012), increase the surface area and wettability alternation (Wang et al. 2010). The nanoparticles are used for Enhancing Oil Recovery (EOR), Table 8 shows the mechanism of nanoparticle (Chegenizadeh et al. 2016). Now there are also nano sensor and nano robots designed for reservoir, which are used for parameters identification and transmission in micro–nano porous media.

The problems and solutions of tight oil exploration in China

According to the exploration evaluation and the pilot test, PetroChina predicted that the tight oil reserves will be 1.5 billion tons, and the productivity construction will be 1.5 million tons in the year of 2020; the number will be

Table 8 Table of mechanism and application of nanoparticle in EOR

Mechanism	Nanoparticle in application
Viscosity reduction	Al_2O_3, CuO, Fe_2O_3/Fe_3O_4, Ni_2O_3, Ethanol and magnesium oxide, Polymer coated nanoparticles
IFT reduction	SiO_2 Nanoparticles, Hydrophobic and lipophilic polysilicon nanoparticles (HLPN), Polyacrylamide micro-gel nano-spheres, Polymer coated nano particles, Ferrofluid
Wettability Alteration	SnO_2, SiO_2 nanoparticles, Alumina coated silica nanoparticles, Hydrophobic silicon oxide, Spherical fumed silica nanoparticles, Neutrally wet polysilicon nanoparticles (NWPN), Lipophobic and hydrophilic polysilicon nanoparticles (LHPN), Polymer coated nano particles
Efficient in sweep and displacement efficiency	Nano-Sized Colloidal Dispersion Gels (CDG), Polymer Nano Particles, Polymer Coated Nano Particles

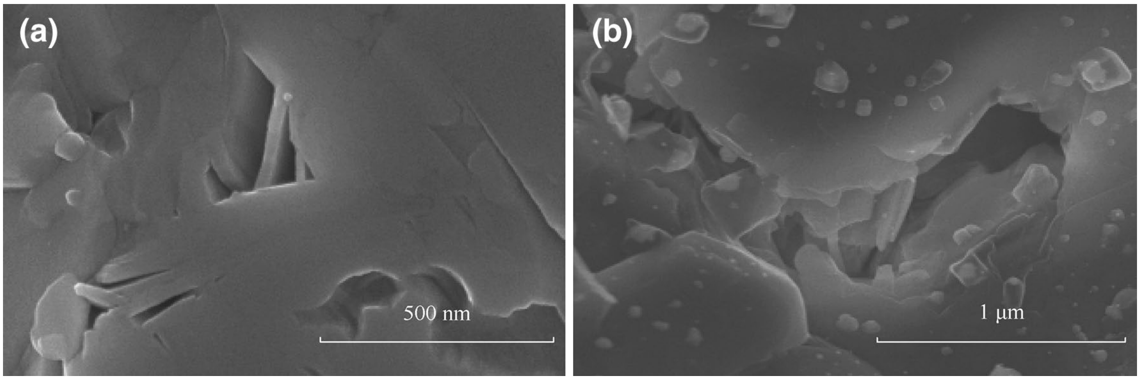

Fig. 2 Microscopic photos of nanopores in tight oil reservoir (Zou et al. 2012). **A** Hechuan1# well in Sichuan Basin, Triassic Xujiahe Formation, tight sandstone intercrystal porosity of clay, pore diameter 25–200 nm. **b** Su315# well in Ordos Basin, upper Paleozoic xiashihezi formation, tight sandstone intergranular pore of quartz, pore diameter 50–250 nm)

6 billion and 10 million tons by the year 2030 (Upstream News Weekly 2018). While China's tight oil development is facing many challenges, the successful experience of North America would not be completely copied (Guo et al. 2011; Huang et al. 2009).

Identification of the dessert area

It is difficult to distinguish the reservoir and non-reservoir, due to the multi-scaled and polygenetic of pore-fracture system in tight oil reservoir, and the differences of physical and mechanical properties of the reservoirs are small. The tight oil reservoirs in China has two characteristics that are continental basin and complex landform. While tight oil formations in North America are based on marine deposits, and widely distributed with bigger thickness and high levels of TOC, the reservoirs are stable with high matrix porosity and under the control of overpressure, the pressure coefficient of oil reservoir is mainly 1.35–1.8 (Gong et al. 2009). Tight oil reservoirs scatter in our country by multiple continents joining together. Most of the reservoirs in southern areas are formed by hilly mountains, thus the identification and classified evaluation of "dessert" are facing challenges (Zou et al. 2013).

Improve the way of formation energy supplement

Complement producing energy is a general problem worldwide. The continental tight oil in China is usually small scale and low production in single well. Water flooding test in Jilin oilfield Honggang tight oil could not set up effective displacement system, dynamic prediction recovery efficiency was low. The dynamic recovery efficiency was only 14.1%, predicted by water flooding curve, the final cumulative oil production was 3500 tons, which was poor in economic performance. The tight oil development should take unconventional development philosophy, in pursuit of the largest single well production and cumulative production, advanced development method and energy supplement method should be studied to improve the tight oil recovery. Therefore, advanced tight oil fracturing technology should be adopted to realize economic development.

Innovation of management system

It is important to innovate management system to promote the large-scale profitable development of tight oil. Marketization is the key to achieving a significant breakthrough in tight oil and gas in North America. Updating the concept of project management and explore the "factory-like" operation. From the conventional oilfield to tight oil reservoir development, first of all, we should realize the conceptual change of reservoirs evaluation, development mode and technique. The essential productive factors of tight oil production are very different from conventional oil, attached more importance to the cycle of fine management. Highly collaborative from multi-type of work such as drilling and completion is needed.

Factory operation is the important still in the stage of exploration. The factory low-cost development pattern of multiple well platform not only improve the working efficiency but also reduce the operation cost, the cost of single well dropped from $2.53 million to $1.9 million, the drilling cycle dropped from 26 days to 10 days. Optimizing resources usage realize 90% of the output water reused, and realize 6 horizontal wells drilled in one platform to reduce the ground occupying space. While our drilling and fracturing machines could not fully meet the requirements for continuous operation, and we are lack of management experience of parallel job, the design of matching and relative technology are also incomplete (Zeng 2009).

Pursuing the policies support

We should actively strive for the relevant policies on the tight oil development support. Many wells of tight oil in China are of low production with high investment of 50 million Yuan or even more, and the drilling cost per meter in depth of 15–20 thousand Yuan. Depreciation according to the law of diminishing and the method of line, the pretax profit of the wells that day production under 15 tons is negative in the first 4 years, and the later production is difficult to sustain. If 30% bonus are turned over during the benefit period, the enterprises will face more severe situation. The successful development of tight oil in America cannot leave the government's policy support, the unconventional oil and gas wells can gain a fiscal subsidiary of $22.05 per ton (or heat equivalent) in 2006–2010.

Conclusions

Although the continental deposits tight oil in China has various degrees of problems, we still can improving the exploration efficiency by strengthening basic research, innovation on technical and management methods, to realize large-scale commercial development.

1. China is rich in tight oil resources and the accumulation condition is superior, tight oil has important status on the replacement resources in future. The early exploration and pilot tests have carried on, prepared for the realization of the scale development.
2. The tight oil reservoirs in China are continental deposition, and there are many types of source rocks, the properties and pressure coefficient are quite different from marine deposit tight oil in North America, thus the successful exploration of North America tight oil cannot fully replicate.
3. There are already some appropriate technology for tight oil exploration, such as seismic, well logging, drilling, hydraulic fracturing technology, and the nanotechnology in process of research, while there are still requirements for the further study of new technology and improved operation to accelerate the exploration of tight oil.
4. We are facing the problems of identifying the dessert and energy complement in tight oil exploration. We should change the development concepts from conventional oilfield exploration to unconventional oilfield, adopting advanced fracturing technology, innovating management system and actively strive for the relevant policies support, to promote profitable development of continental tight oil in China.

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