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PROGRESS IN EXPLORATION, DEVELOPMENT AND UTILIZATION OF OIL SHALE IN CHINA

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Abstract. *The huge oil shale resources in China have gradually attracted widespread attention due to the shortage of oil and gas resources in the country and the rapid recovery of world oil prices. A nationwide prospecting survey of oil shale in China was conducted for the first time during a period from 2003 to 2006, reporting on around 719.9 billion tons of oil shale. After that, many large oil shale deposits have been discovered in the country, and the exploration of oil shale is flourishing. Although the total shale oil production from oil shale of China has been fluctuating due to the low world oil prices in recent years, it, in general, has rapidly increased since 2006 and reached the highest annual production of 8.3 × 10^5 tons in 2015. At present, there are six oil shale production bases in operation in China, and two sets of pilot experiments carried out on oil shale in-situ conversion technology have preliminarily proved to be successful. A green industrial chain including refinery, power generation and building materials production from oil shale in oil shale enterprises has been formed due to the high added value and environmentally friendly impact of oil shale from this chain. Moreover, new insights were gained into the genesis of terrestrial oil shale in China and the characterization of deep lake, shallow lake and limnetic deposited oil shale. These theoretical breakthroughs further enriched the genesis theory of oil shale in continental basins. Although considerable progress has been made*

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in China in the oil shale field both industrially and academically, more work needs to be done to establish a representative oil shale metallogenic model and to accurately evaluate oil shale for its development potential.

Keywords: *Chinese oil shale, exploration and development, production base, genesis study, utilization.*

1. Introduction

Oil shale is commonly defined as a rock containing combustible solid organic matter with a high concentration of ash (inorganic mineral material) which yields shale oil upon low temperature distillation [1–3]. The organic matter is mainly sapropel, humus or the mix of the two. Oil shales vary widely in shale oil yield and gross heating value, the former being typically used to determine their commercial grade [3]. In China, the industrial indicators of oil shale on a dry weight basis are considered to be an oil yield higher than 3.5% and a gross heating value usually higher than 4.18 MJ/kg, which, however, may change depending on economic fluctuations and technological improvements [1].

In recent years, China has increased its investments in the exploration and development of unconventional oil and gas resources due to the long-term shortage of oil and gas in the country and a recent recovery of world oil prices. Among these unconventional petroleum resources, oil shale is especially relevant because it is not only an important type of energy resource that can act as a successor or supplement to conventional petroleum resources, but also has a potential for a comprehensive utilization in fields such as chemical and pharmaceutical industries, building materials production, agriculture, as well as environmental protection, due to its specific composition and structure. Considerable progress has been made in the exploration, evaluation, development and comprehensive utilization of oil shale in China after more than a decade of intensive work. Moreover, new insights have been gained into the genesis of terrestrial oil shale in China and the characterization of deep lake, shallow lake and limnetic deposited oil shale, being an important supplement to the academic oil shale research worldwide. This contribution is to review and summarize the industrial and academic achievements in the oil shale field in China, providing a broader and up-to-date picture of its development in the country.

2. Exploration and evaluation of oil shale in China

The exploration and evaluation of oil shale resources in China has mainly undergone three stages: the initial survey stage in the 1950s and the 1960s, a national prospecting and evaluation stage from 2003 to 2006 and a scattered exploration stage after 2006.

2.1. Initial survey stage in the 1950s and the 1960s

In China, there was a great shortage of energy in the 1950s and the 1960s because no significant breakthrough had been achieved in the petroleum exploration, which contributed to the first climax in oil shale survey during that stage. The oil shale resources were estimated at 2.0485 trillion tons and 400 billion tons, respectively, by the former Ministry of Coal Industry and the Fushun Petroleum Institute in the 1950s and the 1960s [4, 5]. However, these evaluation results are not comparable due to the lack of a unified standard of oil shale resources exploration and evaluation and the existence of many different industrial indicators of oil shale (the lower limit on oil yield of about 3%, 3.5%, 4%, 5%, etc., to consider oil shale as industrial [1]).

2.2. National prospecting and evaluation stage from 2003 to 2006

A national prospecting and evaluation of oil shale was conducted from 2003 to 2006 by the Ministry of Land and Resources of China together with Jilin University, during which oil shale resources were evaluated for the first time according to a unified standard across the country [5]. This prospecting and evaluation included 22 provinces and autonomous regions, 47 basins and 80 rock-bearing areas. The boundary evaluation parameters used were: (i) oil yield higher than 3.5%, (ii) buried depth less than 1000 m and (iii) signal layer thickness of oil shale greater than 0.7 m [5, 6]. The total oil shale resources in China were determined for the first time and were estimated to be 719.9 billion tons with a total of 47.6 billion tons of shale oil [1, 6].

2.3. Scattered exploration stage after 2006

Due to the importance of oil shale in China's energy sector, its exploration has been flourishing especially since 2006. Oil shale exploration and evaluation have been successively conducted by several research institutes in different regions of the country. Of them, achievements of three institutes deserve highlighting.

China Geological Survey jointly with Jilin University carried out the analysis of potential oil shale resources in China in 2009. The geological resources of oil shale were estimated to increase to 739.1 billion tons, and those of shale oil, to 48.7 billion tons (Fig. 1) [7].

Geological Survey Institute of Jilin Province proved four super large oil shale deposits in the Songliao Basin, Northeast China during 2006 to 2010, which are located in Fuyu-Changchunling, Qianguo-Nongan, Sanjingzi-Dalinzi and Shenjingzi areas. With identified 101.878 billion tons, the Songliao Basin is China's richest basin in oil shale resources [8].

The 1st Regional Geological Survey Team of Xinjiang Geology and Mineral Bureau conducted works on oil shale prospecting and evaluation in Shichanggou-Bayanghe-Mutasi-Wujiawan region in the years 2006–2014,

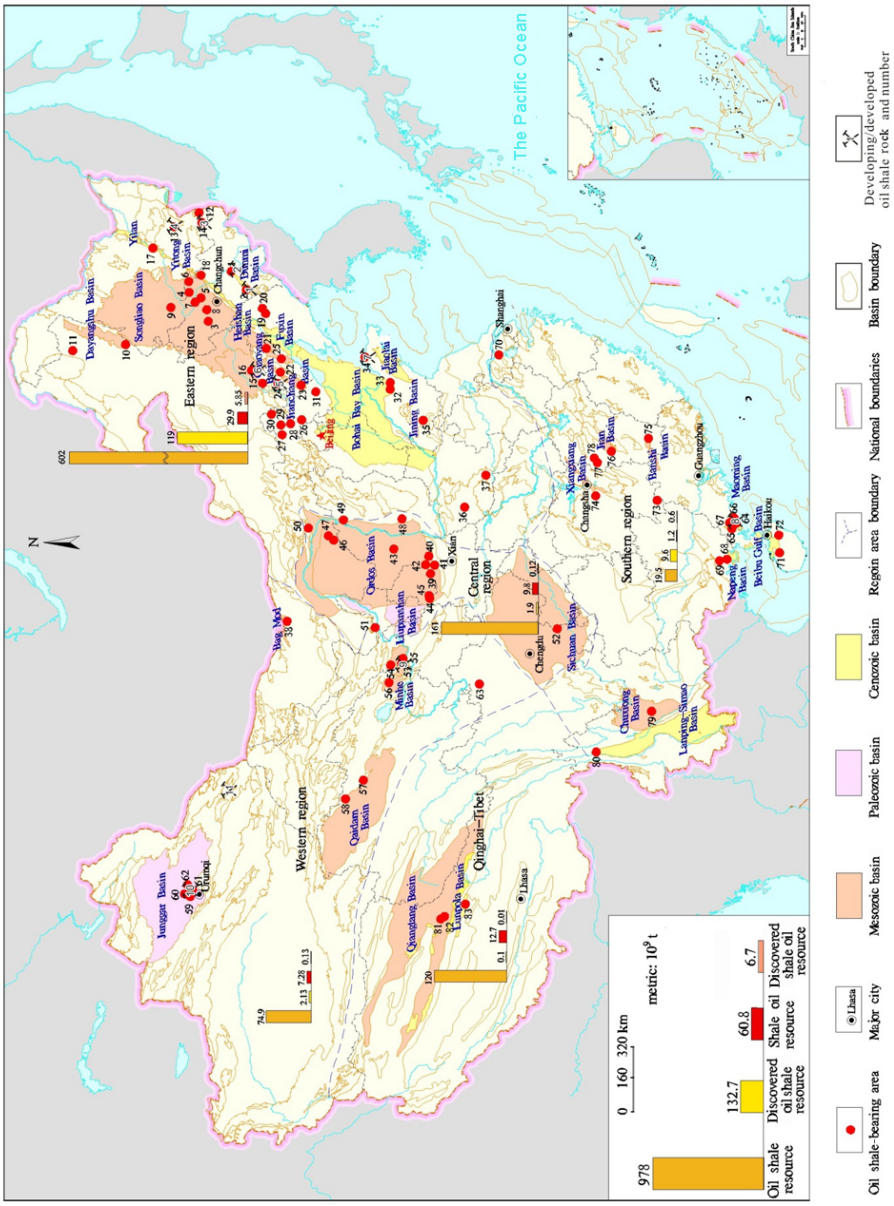
The Pacific Ocean
Eastern region
Central region
Western region
Southern region
Qinghai–Tibet
Oil shale resource
Discovered oil shale resource
Shale oil resource
Discovered shale oil resource
978
132.7
60.8
6.7
metric: 10^9 t
0 160 320 km
Oil shale-bearing area
Major city
Mesozoic basin
Paleozoic basin
Cenozoic basin
Region area boundary
National boundaries
Basin boundary
Developing/developed oil shale rock and number

Fig. 1. Distribution of oil shale resource and developing/developed oil shale rock in China (modified after [6]). Oil shale-bearing areas: 1 – Huadian; 2 – Meihe; 3 – Changling; 4 – Fuyu-Changchunling; 5 – Qianguo-Northern Nong'an; 6 – Sanjingzi-Dalinzi; 7 – Shenjingzi; 8 – Xiaohelong; 9 – predicted area of Songliao Basin; 10 – A'Rongqi; 11 – E'Lunchun; 12 – Laoheishan; 13 – Linkou; 14 – Luozigou; 15 – Aohanqi; 16 – Naiman; 17 – Dalianhe; 18 – Shulan; 19 – Fushun; 20 – Shimenzhai; 21 – Fuxin; 22 – Chaoyang; 23 – Jianchang; 24 – Lingyuan; 25 – Yixian; 26 – Dage; 27 – Sichakou; 28 – Fengshan; 29 – Qingquan; 30 – Jiangjiaying; 31 – Lulong; 32 – Changle; 33 – Anqiu; 34 – Huangxian; 35 – Yanzhou; 36 – Luanchuan; 37 – Tongbaiwucheng; 38 – Bagemaode; 39 – Binxian; 40 – Tongchuan; 41 – Chunhua; 42 – Intra-Binxian and Tongchuan; 43 – Intra-Tongchuan and Zichang; 44 – Huating; 45 – Congxin; 46 – Yijinhuoluoqi; 47 – Dongsheng; 48 – Puxian; 49 – Baode; 50 – Shiguai; 51 – Zhongning-Zhongwei; 52 – Yibin-Neijiang; 53 – Yaojie; 54 – Tanshanling; 55 – Haishiwan; 56 – Xiaoxia; 57 – Dameigou; 58 – Yuqia; 59 – Yuqia; 60 – Yaomoshan; 61 – Lucaogou; 62 – northern margin of Bogda Mountain; 63 – A'Ba; 64 – Maoming; 65 – Gaozhou; 66 – Dianbai; 67 – predicted area of Maoming Basin; 68 – Napeng; 69 – Qinzhou; 70 – Jintan; 71 – Danzhou; 72 – Changchang; 73 – Ningyuan; 74 – Xiangxiang; 75 – Aanyuan; 76 – Aocheng; 77 – Pingxiang; 78 – Yichun; 79 – Chuxiong; 80 – Weixi; 81 – Tongbori; 82 – Biluocuo; 83 – Jiangjiacuo.

Developing/developed oil shale rock number: 1 – Fushun oil shale rock; 2 – Huadian oil shale rock; 3 – Luozigou oil shale rock; 4 – Linkou oil shale rock; 5 – Linyuan oil shale rock; 6 – Beitazi oil shale rock; 7 – Longkou oil shale rock; 8 –Maoming oil shale rock; 9 – Yaojie Oil shale rock; 10 – Baoming oil shale rock; 11 – Taimou oil shale rock.

which is in the north of Bogda Mountain in the Junggar Basin, Northwest China. The oil shale resources in that area were estimated at 59.169 billion tons, of which the discovered resources accounted for 1.846 billion tons [9]. This has motivated several companies to carry out oil shale mining in the explored area.

Further achievements in the prospecting and evaluation of oil shale in China can be summarized as follows. The Daqing Oilfield of China National Petroleum Corporation (CNPC) carried out an oil shale resource survey in the northern Songliao Basin and the Liushuhe Basin, Northeast China in 2006 [10–12]. The Tuha Oilfield of CNPC in Bag Mod discovered a new oil shale-bearing area, in Inner Mongolia of North China in 2007 [7]. Henan Bureau of Geo-exploration and Mineral Development carried out oil shale exploration in Tongbai County, Henan Province of East China in 2007 [7]. The Oil and Gas Survey of China Geological Survey and China University of Geosciences (Beijing) conducted an oil shale survey in the Santanghu Basin, the Turpan-Hami Basin and the Tarim Basin from 2006 to 2015 [9, 13, 14]. The Oil and Gas Survey of China Geological Survey and Jilin University characterized the distribution of oil shale in the Songliao Basin and the Laoheishan Basin in Northeast China and the Qaidam Basin in Northwest China in the years 2012–2017 [9, 15–23]. The Chengdu Center of China Geological Survey has carried out an oil shale survey and evaluation work in the Tibet region of Southwest China during many years [24–36].

3. Development of oil shale in China

3.1. The production of shale oil from oil shale

The shale oil industry set up in Fushun of Liaoning Province in China in 1928 represents the country's first industry of this kind [5]. Since then, the oil shale development in China has been continuing during more than 80 years and entered a new stage in the beginning of the 21st century with the rise of global oil prices and the progress made in national oil shale resource evaluation in 2003–2006 [1, 37]. The oil shale development in China has generally presented a situation of "continuous increase in the production of shale oil" and "simultaneous reconstruction, introduction and independent innovation of retorting technology" [38]. The shale oil production in the country hit a new high in 2015, reaching 830,000 tons [39], though it experienced a slight decline in 2016 due to low world oil prices (Fig. 2). At present, due to an increasing demand for unconventional energy in China, the exploration for oil shale resources continues to increase. In terms of oil shale development and utilization, China has been not only continuously seeking new advanced retorting technologies, but is also progressing towards an "environmentally friendly" approach, which includes the full utilization of oil shale.

3.2. Oil shale production bases

In the years 2000–2017, China had 11 active oil shale production bases which were mainly located in Northeast, East and West China. Of these, six bases are still in operation currently (Fig. 1). Below a brief overview of the 11 production bases will be given.

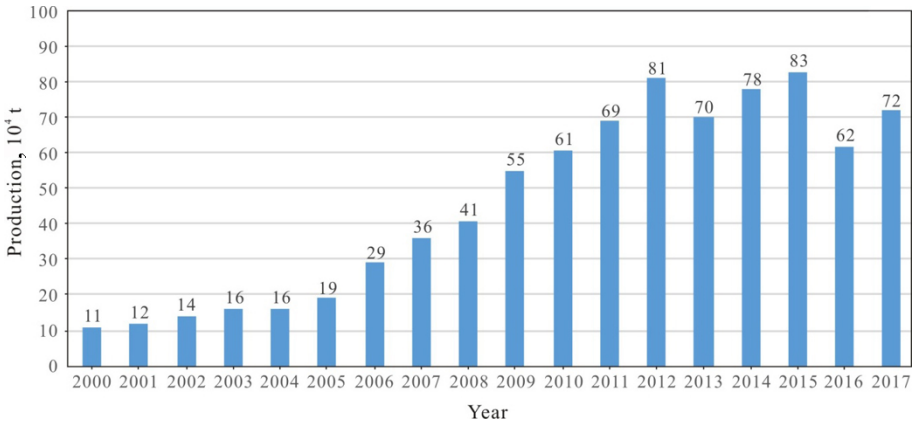

Fig. 2. Production of retorting oil from oil shale in China, 2000–2017.

3.2.1. Northeast China

3.2.1.1. Fushun Oil Shale Mine, Liaoning Province (in operation)

The Oil Shale Refinery of Fushun Mining Group is in Liaoning Province, Northeast China [1]. It was founded in 1928 and is China's oldest and largest oil shale production base [1]. The oil shale of this mine is a thick continuous deposit (maximum thickness 195.5 m), with good quality and shallow burial depth, and is suitable for open-pit mining [40]. Fushun Mining Group has currently 220 Fushun furnaces in operation, which process 100 tons of oil shale per day. The annual production of shale oil is about 500,000 tons. In recent years, this company has introduced and assembled Alberta Taciuk Process (ATP) particle shale retorts, which enables an efficient use of 60,000 tons of small-particle oil shale.

3.2.1.2. Huadian Oil Shale Mine, Jilin Province (closed)

Huadian Oil Shale Mine is located in Jilin Province, Northeast China. No. 9 Petroleum Factory of Northeast China was founded in this mine for oil shale retorting in 1953, and several companies jointly exploited oil shale mines in this area after that. Huadian oil shale has a thin monolayer thickness (1–3 m), a high oil yield (up to 24.8%) and a small strata dip angle (less than 20°). The Huadian Oil Shale Mine adopted the underground roadway for mining

[1]. Since the beginning of the 21st century, these companies used 34 Fushun retorts which could produce 70,000 tons of retorting oil per year. The companies built several small-particle shale circulating fluidized bed combustion boilers for commercial power generation and turned the ash of oil shale into building materials. A comprehensive development and utilization industrial chain was created, which incorporated oil shale mining, oil shale retorting, semi-coke power generation and building materials production. However, the development of Huadian oil shale has stopped due to the low global oil prices and depletion of oil shale resource.

3.2.1.3. Luozigou Oil Shale Mine, Jilin Province (in operation)

The development and utilization of oil shale in Luozigou of Jilin Province began in 1958 [1]. The company that currently exploits oil shale in Luozigou mine is Jilin Wangqing Longteng Energy Development Co., Ltd. Oil shale in this area is of medium thickness (8–15 m), medium quality (average oil yield is 6.04%) and small dip angle (mine slope is generally less than 6°. The company employs the underground roadway method. By present, Jilin Wangqing Longteng Energy Development Co., Ltd. has built 20 Fushun retorts, which can produce 50,000 tons of retorting oil per year. To further extend the oil shale industry chain, the company has completed a series of projects including (i) using small-particle oil shale for power generation, (ii) making the generated ash from power generation into cement and (iii) using the waste residue produced by retorting to make bricks. In this way, this company has achieved a goal of using oil shale in an economical, environment-friendly and efficient way.

3.2.1.4. Mudanjiang Linkou Oil Shale Mine, Heilongjiang Province (in stagnation)

Mudanjiang Linkou Oil Shale Mine is located in Heilongjiang Province, Northeast China, which was built mainly for a pilot production of oil shale by the Daqing Oilfield of China National Packaging Corporation (CNPC). In 2008, Daqing Oilfield adopted a technology of particulate oil shale retorting by solid heat carrier which was developed by Dalian University of Technology to test the retorting of Linkou oil shale rock in the Mudanjiang Basin. Some technical challenges coupled with the impact of low global oil prices have brought the project currently in a state of stagnation.

3.2.1.5. Lingyuan Oil Shale Mine, Liaoning Province (closed)

In 2014, Liaoning Lingyuan Aoyi New Energy Co., Ltd. launched a two-year project on the use of 3 million tons of oil shale in Wujiazi area annually for retorting and comprehensive utilization. However, due to the accompanying environmental pollution and low global oil prices, the project was stopped in 2016.

3.2.1.6. Beipiao Beitazi Oil Shale Mine, Liaoning Province (in operation)

Beitazi Oil Shale Mine is located in Beipiao of Liaoning Province, Northeast China. Oil shale is mainly mined by Zhejiang Hailiang Group and Northern Liaoning Coal Mining Group. Beitazi Oil Shale Mine started operation in 2009, but was closed in 2015, and was opened again in June 2017. At present, 150 tons of oil shale rock is utilized every day, the annual output of shale oil is 60,000 tons.

3.2.2. East and South China

3.2.2.1. Longkou Oil Shale Mine, Shandong Province (closed)

Longkou Oil Shale Mine is in the coastal area of Shandong Province, East China. Oil shale mining and utilization began here in 2006, and in the first years, 73,000 tons of shale oil per year was produced. By 2012, the mine was able to process 2.5 million tons of oil shale annually, of which 50% was used for oil retorting and 50% for power generation. At the same time, the annual shale oil production had increased to 120,000 tons. However, due to the impact of low global oil prices, the oil shale development in Longkou mine was stopped in September 2016.

3.2.2.2. Maoming Oil Shale Mine, Guangdong Province (closed)

In South China, only oil shale in the Maoming Basin of Guangdong Province has been developed and utilized. The production of oil shale in the basin started in 1962 [1]. In the beginning, Maoming Oil Shale Mine mainly used oil shale and lignite for oil retorting, producing nitrogen water and generating electricity. Due to environmental pollution problems, the mine was closed in 1993. Having started in 2013, the construction of an eco-park in this former opencast mining area has been completed by now and the park is open to the public.

3.2.3. West China

3.2.3.1. Yaojie Oil Shale Mine, Gansu Province (in operation)

Yaojie Oil Shale Mine is located in Gansu Province, West China. The development and utilization of oil shale started in 2010. The company has today eight SJ-IV type square furnaces in operation with a daily processing capacity of 500 tons of oil shale by a single furnace and an annual total processing capacity of 1.25 million tons of oil shale. At present, the production of shale oil amounts to 50,000 tons per year. There are also 30 gas-fired power generating units with a capacity of 500 kW per unit in operation. Yaojie Oil Shale Mine has been consistently making profit from oil shale development.

3.2.3.2. Baoming Oil Shale Mine, Xinjiang Uygur Autonomous Region (in operation)

Baoming Oil Shale Mine is in the north of Bogda Mountain in Xinjiang Uygur Autonomous Region, West China. The preparations for oil shale development and utilization started in 2005. Currently, Baoming Oil Shale Company operates 64 retorting furnaces that can process 320,000 tons of oil shale annually. The annual shale oil production from oil shale has risen to 100,000 tons. However, due to the low world oil prices, the mine stopped oil shale production and is at the moment in the beneficiation test phase. The latest news reveals that Baoming Oil Shale Company plans to recommence production of oil shale in 2019.

3.2.3.3. Taimu Oil Shale Mine, Xinjiang Uygur Autonomous Region (in operation)

Taimu Oil Shale Mine is in Balikun County in Xinjiang Uygur Autonomous Region, West China. In 2013, the company completed preparations for a project aiming to produce 60,000 tons of shale oil from oil shale. The project was officially launched in 2015 and the annual production of retorting oil has been gradually increased since then. In 2017, the company processed 1.4 million tons of oil shale and produced 60,000 tons of retorting oil. At present, it makes considerable profit.

3.3. Oil shale in-situ conversion

China has developed two types of technologies for the in-situ conversion of oil shale based on its characteristics, and small-scale experiments on these technologies have proved successful. At the same time, four indoor technologies for oil shale in-situ conversion have also been worked out in the laboratory.

3.3.1. On-site experimental technique for in-situ conversion of oil shale

The technologies for the on-site experiments on oil shale in-situ conversion in China have been developed by Zhongcheng Group and Jilin University, and the outcome has been favourable.

3.3.1.1. In-situ chemical fracturing technique for oil shale extraction (Zhongcheng Group)

The in-situ experiment on the chemical fracturing for oil shale extraction was carried out by Zhongcheng Company in Fuyu City of the southern Songliao Basin, Jilin Province, Northeast China. The oil shale at a depth of nearly 300 m was ignited in July 2014. After 10 days of stable combustion, the first barrel of in-situ shale oil in China was successfully extracted by this company [41]. This technology fills China's gap in the field of oil shale in-situ technology. In three months the cumulative shale oil production was

5.2 tons, with a maximum daily production of 355 kg. A medium-scale (pilot) test was conducted in July 2015. Retorting oil was obtained after ignition and the maximum daily output of a single well exceeded 200 kg.

3.3.1.2. Improved topochemical heat technique for oil shale in-situ conversion (Jilin University)

Jilin University successfully exploited the high-quality shale oil obtained in-situ from oil shale in Nong'an County in the southern Songliao Basin, Jilin Province of Northeast China in 2015 [42]. Such success has benefitted from two years of scientific research by Jilin University, during which a series of key technical problems were solved, including the shallow layer fracturing and heat transfer at high temperature, heat insulation, groundwater intrusion and pollution diffusion, etc. At present, Jilin University is carrying out medium-scale (pilot) tests on in-situ conversion of oil shale in Fuyu City of Jilin Province.

3.3.2. Indoor experimental technique for in-situ conversion of oil shale

Jilin University extracted organic matter from oil shale at elevated temperature and under high pressure by using the technology for oil shale in-situ extraction in subcritical water in the laboratory. The experiment showed that during the extraction of organic matter also a certain amount of gas could be obtained in a short time under the conditions of relatively low temperature (260 °C) and high pressure (14.5 MPa). With increasing critical water temperature the intensity of extraction gradually increased, reaching maximum at a temperature of 350 °C [43].

Meanwhile, Jilin University invented the high voltage-power frequency electrical heating method for oil shale pyrolysis. In the simulation experiment, the electric arc of the high voltage electric breakdown promotes the production of heat. As the internal heat continues to accumulate, the resistivity between two heating electrodes of oil shale is reduced gradually. Then oil shale is gradually heated and a conductive path is formed, as a result of thermal breakdown. In this way, the heating carrier is formed in the conductive heat channel, the temperature exceeds 400 °C, and the organic matter around oil shale is gradually pyrolyzed [44].

Jilin University has also carried out research on oil shale pyrolysis triggered by topochemical heat. In this method, the pyrolysis represents a chemical rather than a physical heating process. There is an obvious thermal expansion in the process of oil shale pyrolysis induced by topochemical heat, especially at a temperature between 300 and 550 °C. The porosity and permeability of oil shale increase quickly and the ordering of pore structure in semi-coke becomes obvious during a high-temperature stage. In general, this method has advantages of low energy consumption, easy reaction, and controllable and high oil yield [45].

Taiyuan University of Technology developed a convection heating technology. This method uses the fracturing technology to connect the heated well and the producing well. The high-temperature hydrocarbon gas (400–700 °C) is injected in the oil shale layer and will heat it via convection, thus promoting the removal of hydrocarbon during pyrolysis [46–48].

4. Comprehensive utilization of oil shale in China

At present, oil shale in China is mainly used for retorting oil or generating electricity. The oil shale ash cannot be utilized if oil shale is only used for retorting. The energy efficiency in this case is very low (only 40–50%) and the environmental pollution is serious. Similarly, a lot of oil will be wasted if oil shale is only used for burning to generate electricity. The single-purpose utilization mode not only brings about a huge waste of oil shale resources and causes serious environment pollution, but also considerably hinders the development of the oil shale industry. In view of the above, many Chinese scientific research institutes have carried out investigations, with promising results, on oil shale waste ash use and put forward ways of oil shale comprehensive utilization.

Liu et al. [1] proposed to extract silica (nanometer scale), aluminum oxide and other compounds from oil shale ashes, which could be used to manufacture building materials such as marble and hollow bricks. Bao et al. [49] tried to extract heavy metals from oil shale ashes. This technique was successfully subjected to laboratory tests and a patent was granted on it. However, due to its high cost and poor economic efficiency, the method has not yet been industrially implemented.

At present, many oil shale companies in China have put forward specific patterns for oil shale development and comprehensive utilization, taking into account local situation and characteristics of ash. These patterns have generally a similar workflow. The large-particle oil shale is used for retorting to produce shale oil. Meanwhile, part of the obtained gas is directed to power plants to generate electricity, while part of it is returned to the furnace to heat the furnace body. Small-particle oil shale can be used for generating electricity directly and the tailings are made into hollow bricks, cement and other building materials, or chemical fertilizers [50–56]. The comprehensive utilization of oil shale can help make full use of oil shale resources, and realize the economical optimization of its environment-friendly comprehensive utilization.

5. Research of the genesis of oil shale in China

Differently from large marine oil shale deposits in many countries like Russia, Estonia, etc., oil shale in China is a continental deposition and its

metallogenic conditions have specific characteristics [1, 57]. So far, studies of the genesis of Chinese terrestrial oil shale have shown that these oil shales are mainly deposited in three kinds of sedimentary environments: deep lake, shallow lake and limnetic setting [57]. Deep lake deposited oil shale is mainly distributed in the Songliao Basin, the Fushun Basin and the Jungger Basin, and its origin has been relatively extensively studied [14, 58–63]. Shallow lake deposited oil shale is predominantly developed in the Huadian Basin, the Luozigou Basin and the Yilan Basin [58, 64–69]. Limnetic deposited oil shale is found in the Laoheishan Basin, the Huangxian Basin and the Minhe Basin, etc. [21–23, 70–73].

5.1. Deep lake deposited oil shale

Oil shale of this type is generally deposited in deep lake to half-deep lake. This environment has a lower supply of terrigenous debris and is mainly composed of fine-grained clay and organic matter deposits. The organic matter is mostly lake algae. The water background during oil shale deposition is salt water or fresh water. However, the environment of the lake bottom is basically anoxic, which provides good preservation conditions for the enrichment and preservation of organic matter. This type of oil shale deposit is usually of wide distribution, the respective area may amount to tens of thousands of square kilometers [57, 62, 65, 74–77].

5.2. Shallow lake deposited oil shale

The sedimentary environment of this oil shale is generally half-deep lake to shallow lake. This environment has a certain amount of terrigenous debris supply and mainly accumulates fine-grained clay, organic matter and a small amount of debris particles. The organic matter is chiefly composed of lake algae and sporophytes, as well as a small amount of land-derived higher plants. The water background during oil shale deposition is mostly freshwater with oxygen-depleted lake bottom. A relatively high sedimentation rate and better preservation conditions contribute to the burial of organic matter. Oil shale deposits of this type are mostly affected by the base level and basin scale, indicating that the higher base level and the larger deep-water area of the fault basin may lead to a wider distribution of oil shale [64, 65, 67, 69, 78].

5.3. Limnetic deposited oil shale

This kind of oil shale is mostly deposited in a limnetic environment. Oil shale is formed during swamp flooding and is interbedded with coal. Oil shale mainly consists of clay, organic matter and a small amount of debris particles. The organic matter comes predominantly from shallow aquatic organisms and land-derived higher plants. The water background during oil shale deposition is mostly freshwater and an oxygen-bearing environment. A relatively high sedimentation rate and high supply of organic matter

contribute to its enrichment. The distribution of limnetic deposited oil shale tends to be limited and with great lateral variations [21–23, 40, 70–72].

6. Future work

Despite the aforementioned achievements, the exploration of oil shale in China is still at low level and the resources discovered are small. The existing technology for the development and utilization of oil shale is not applicable to oil shale of medium quality and deeper burial and the oil shale in-situ conversion has not been subjected to pilot plant tests. It will still take a long time to put oil shale in China into industrial production. Moreover, the added value of oil shale remains to be further developed, which is now limited by its geographical environments and challenges in the comprehensive utilization technology. Academically, the genetic classification of terrestrial oil shale needs to be studied on a national level to create an effective and widely applicable genesis model of oil shale.

7. Conclusions

The exploration and development of unconventional energy are of high strategic significance due to the shortage of conventional energy in China. In the past ten years, great progress has been made in the characterization, metallogenic theory, resource evaluation, development and utilization of oil shale in the country. This contribution reviews the current situation of exploration and development of oil shale in China, which may provide support for the development of oil shale industry in this country and those with similar cases.

1. The total oil shale resources in China were determined for the first time by a nationwide prospecting and evaluation of oil shale during the period from 2003 to 2006, and were estimated to be 719.9 billion tons. Since then, several large oil shale deposits have been discovered, and the oil shale exploration is flourishing.
2. The production of shale oil from oil shale in China has been generally increasing since 2006, though there was a slight decline due to the low world oil prices in the meantime. In 2015, the maximum annual production of shale oil amounted to 830,000 tons.
3. There were 11 oil shale development and utilization bases in China in the years 2000–2017. Six bases are currently in operation and are mainly located in Northeast and West China. Meanwhile, two sets of pilot experiments have been carried on oil shale in-situ conversion technology, and four kinds of indoor experimental techniques have been tested, with promising preliminary results. To meet China's environmental protection requirements and survive in the conditions of low

world oil prices, a green chain of oil shale development and utilization has been created, which incorporates oil refining, power generation and building materials production.

4. Research on the genesis of Chinese terrestrial oil shale is progressing, and good results have been obtained in the theory of mineralization of deep lake, shallow lake and limnetic deposited oil shale. This will provide a scientific guidance for the exploration for oil shale in the basins of the same type, but with a lower degree of exploration.

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