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CHARACTERISTICS AND COMPREHENSIVE UTILIZATION POTENTIAL OF OIL SHALE OF THE YIN'E BASIN, INNER MONGOLIA, CHINA

RONG LIU[(a,b)*], ZHAOJUN LIU[(a,b)*], WEI GUO[(a,b)],
HUIJUN CHEN[(c)]

[(a)] College of Earth Sciences, Jilin University, 130061 Changchun, China
[(b)] Key Laboratory of Oil Shale and Coexistent Energy Minerals of Jilin Province, 130061 Changchun, China
[(c)] Shenyang Institute of Geologic and Mineral Resources, CGS, 110034 Shenyang, China

Abstract. *The Yin'e Basin is an important oil shale-bearing deposit in the Bagemaode area of Inner Mongolia province, Northern China. Oil shale developed in the Bayingebi Formation of the Mesozoic Lower Cretaceous belongs to mudstone shales. In addition to rich organic matter, it also contains detrital minerals like quartz and feldspars, as well as clay minerals like kaolinite, andreattite and illite, with an average content of 45% (detrital minerals) and 37% (clay minerals). Analysis of mineral abundances in oil shale showed that the contents of* SiO_2 *and* Al_2O_3 *were relatively high, the respective averages being 46.99% and 13.67%. The oil shale is rich in metal elements such as Sr, Cs, Zn, Rb, Pb and Co, as well as rare earth elements. The highest oil yield of the oil shale in the research area is up to 15.3%, with an average of 4.72%; its average ash content is 77.38% and average calorific value 3.82 MJ/Kg. Based on the above figures, the oil shale can be regarded as a rock with low-medium oil yield, high ash content and low calorific value. Resource evaluation showed that the proved reserves of Bagemaode oil shale are 3.976 billion tons, which are generally considered a rich resource and are characterized by a shallow burial depth. In view of the above different characteristics of oil shale and in consideration of environmental and economic factors, this paper proposes that a multiple-approach and multiple-combination comprehensive development and utilization of Bagemaode oil shale through retorting–power generation–production of metals, silica and building materials should be achieved.*

Keywords: *oil shale, Yin'e Basin, Bagemaode area, resource potential, comprehensive development and utilization potential.*

* Corresponding author: e-mail *jpuliurong@163.com; liurong@jlu.edu.cn*; *liuzj@jlu.edu.cn*

1. Introduction

Oil shale (also known as kerogen shale) is a solid combustible organic sedimentary rock with a high ash content, an oil yield higher than 3.5%, and a calorific value generally greater than 4.18 MJ/kg. It can be used to produce shale oil through retorting at low temperature. In the development and utilization of oil shale, its industrial standards may vary with changes of economic and technological conditions [1]. Due to the shortage of conventional oil and gas, unconventional types of energy like oil shale, shale gas and shale oil have attracted extensive attention in many countries worldwide lately. A large-scale development and utilization of oil shale has been conducted in China, Estonia, Brazil and other countries with significant economic benefits [2]. In 2003–2006, a nationwide resources evaluation of oil shale was carried out in China. The evaluation showed that China is rich in oil shale, which is mainly distributed in the 80 oil shale deposits of 47 basins in 20 provinces (municipalities and autonomous regions), with total resources of 719.9 billion tons, of which the proved reserves are 50 billion tons, accounting for 69.56% of their total [3]. In recent years, with the continuous exploration of oil shale resources, a number of new oil shale-bearing basins and deposits have been found in China. The Yin'e Basin is one of such deposits with oil shale developed in the strata of the Bayingebi Formation of the Mesozoic Lower Cretaceous (K_1b), Bagemaode area, Inner Mongolia, Northern China. This article examines the comprehensive development and utilization potential of Bagemaode oil shale, based on the analysis of its characteristics and evaluation of resources.

2. Geological background and distribution characteristics of oil shale

The studied oil shale lies in the Bagemaode Depression, the secondary unit of Chulu Uplift, in the northeast corner of the Yin'e Basin, Inner Mongolia of Northern China. The Yin'e Basin, extending on an area of about 120,000 km^2 with a west-east length of 700 km and a north-south width of 75–225 km, is bounded by Langshan Mountain on the east, by Yabulai Mountain on the south, by North Mountain on the west and by the Sino-Mongolian border on the north (Fig. 1) [4, 5]. The Yin'e Basin underwent three tectonic evolution stages, namely the early stage of initial faulting, the middle stage of intensive faulting and the late stage of shrinking. Oil shale, with a gross thickness of 35 m, is distributed on an area of 520 km^2 with a west-east length of 29 km and a north-south width of 15–20 km [6, 7]. Oil shale was developed in the Bayingebi Formation of the Mesozoic Early Cretaceous (K_1b) [5]. The research area is mainly divided into four formations, namely oil shale layer 1, oil shale layer 2-1, oil shale layer 2-2 and oil shale layer 3, mostly deposited in the second section (K_1b_2), the third

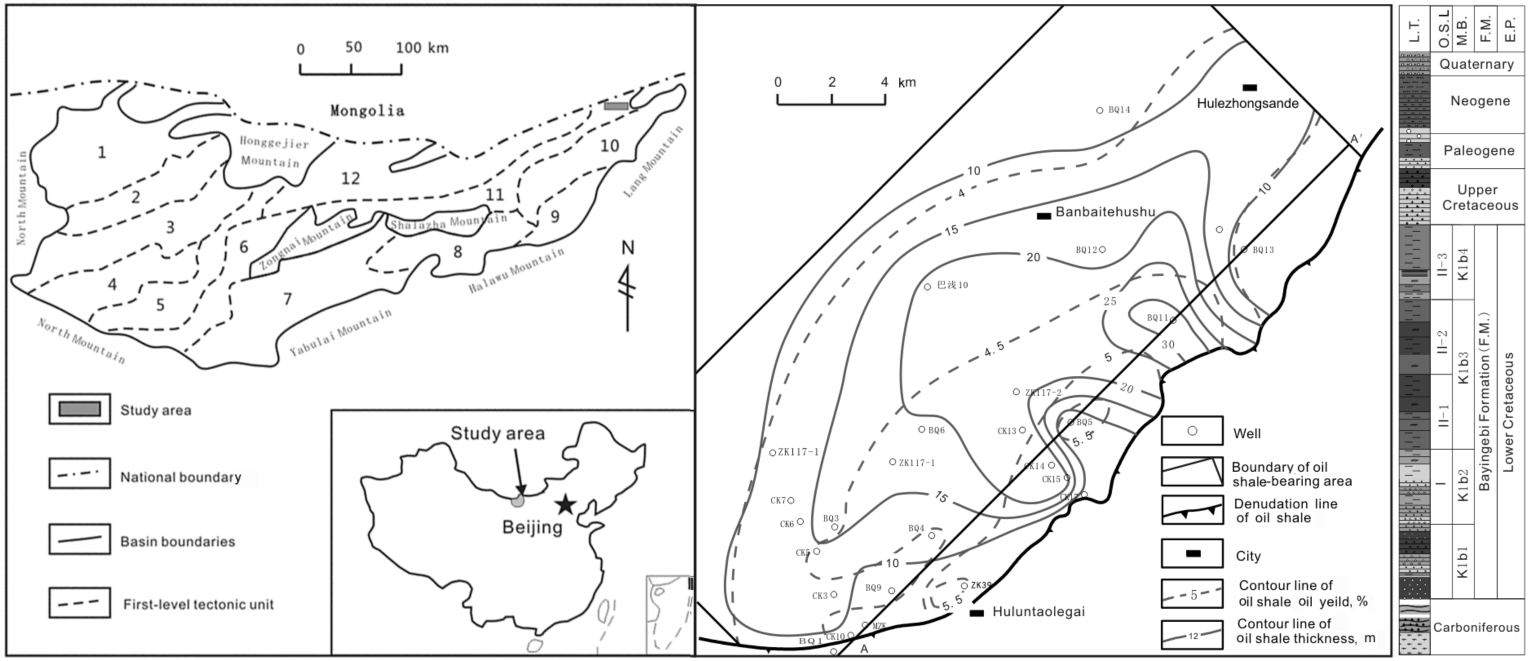

Fig. 1. Location of the Yin’e Basin and distribution of Bagemaode oil shale.

1. Juyanhai Depression; 2. Lvyuan Uplift; 3. Wutaohe Depression; 4. Teluoxitan Uplift; 5. Dagu Depression; 6. Zongnaishan Uplift; 7. Suhaitu Depression; 8. Shangdan Depression; 9. Batu Uplift; 10. Chagandelesu Depression; 11. Chulu Uplift; 12. Sutuhong Depression. (L.T. – lithology; O.S.L. – oil shale layer; M.B. – Member; F.M. – Formation; E.P. – era/period).

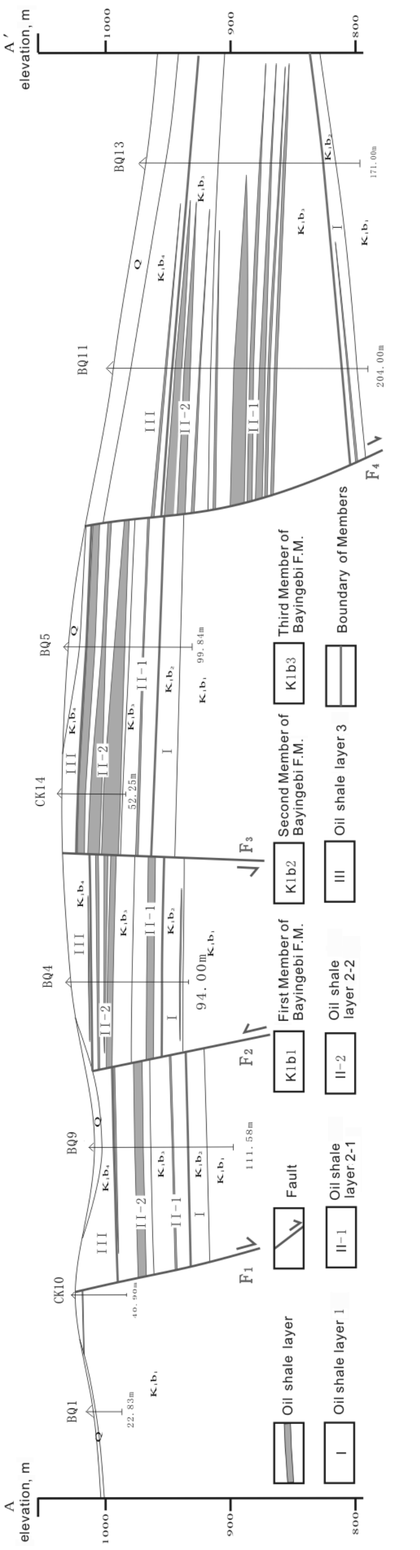

Fig. 1. (Continued).

section (K_1b_3), and the fourth section (K_1b_4) of the Bayingebi Formation. Oil shale layers 2-1 and 2-2 are the main layers of the rock, both developed in the three sections of the Bayingebi Formation (Fig. 1). Generally, the overburden of oil shale is thin, its thickness ranging from 0 to 187.4 m, while that of the main oil shale layers is from 13.8 to 146.50 m. In the research area, oil shale layers with a small thickness prevail and these are mostly distributed in the southeastern and central parts of the mining area. The gross thickness of oil shale towards the southwest, northwest and northeast gradually decreases. The thickness of oil shale layers varies greatly, especially that of adjacent drilled oil shale, which is distributed as layer, layer-like formation or lens (Fig. 1). The oil yield of the studied oil shale changes with thickness. Oil shale with high oil yield is found in the southwest and south of the mining area, while towards the southwest, northwest and northeast the oil yield gradually decreases.

3. Petrologic characteristics of oil shale

3.1. Macroscopic characteristics

Currently, the rock types of oil shale in the world are mainly shale (mudstone), marlstone and carbonate [8]. The oil shale in the research area belongs to the mudstone shale type. Oil shale from coring is mostly dark gray, black gray and grayish brown in colour. In some parts of the Yin'e Basin, oil shale is rich in conchostracans and algal fossils (Fig. 2). Generally,

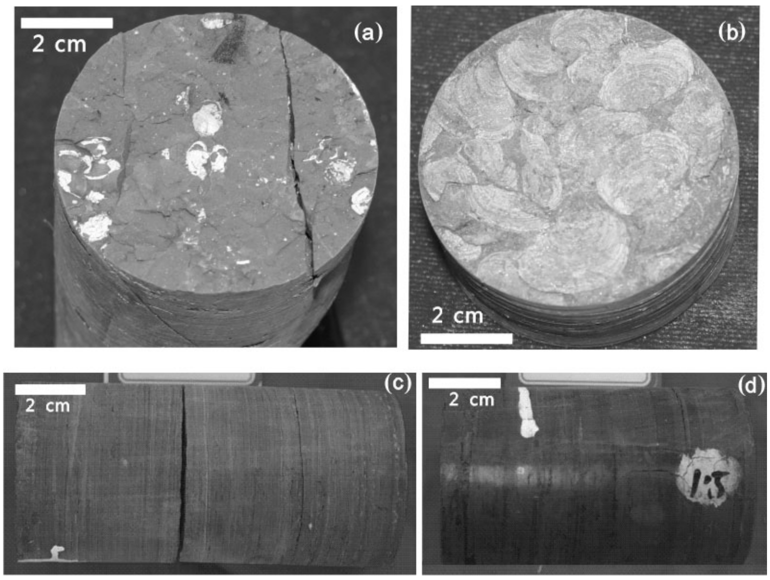

Fig. 2. Oil shale of Bagemaode area: (a) gray oil shale (well BQ4, 30.4 m); (b) dark gray oil shale and conchostracans fossil (well BQ4, 79.7 m); (c) dark gray oil shale (well BQ12, 123.4 m); (d) grey brown oil shale (well BQ12, 100.2 m).

the oil yield of gray oil shale is 3.5–5%, that of dark gray oil shale is 5–10%, and the oil yield of grayish brown oil shale is more than 10%.

3.2. Mineral composition

In addition to rich organic matter, oil shale also contains abundant inorganic mineral components. The qualitative and quantitative X-ray diffraction analysis established that its major minerals include detrital minerals like quartz and feldspars, with an average content of 45%, as well as clay minerals like kaolinite, andreattite and illite, with an average content of 37% (Table 1).

Table 1. Mineral contents in oil shale from the Yin'e Basin

Sample No.	Relative content of minerals, %											
	Clay mineral				Detrital material of terrigenous origin			Other minerals				
	K	I/S	I	Ch	Q	Fs	Pl	Sid	Py	Cc	Do	An
	Kaolinite	Andreattite	Illite	Chlorite	Quartz	Potassic feldspars	Plagioclases	Siderite	Pyrite	Calcite	Dolomite	Analcite
11-1		14	16	4	37	6	7	1	1	14	–	–
11-16	3	13	18	4	35	5	6	–	–	10	–	6
11-24	2	12	15	4	29	3	8	–	1	12	14	–
11-44	2	17	18	4	35	6	8	1	1	4	4	–
11-56	1	12	19	4	25	7	7	1	–	6	6	12
11-93	4	16	15	5	32	6	7	–	–	15	–	–
Average	2	14	17	4	32	6	7	1	0	10	4	3
	37				45			18				

4. Petrogeochemical characteristics of oil shale

4.1. Chemical composition

On the basis of analysis and test results, the Bagemaode oil shale may be characterized by a relatively high content of Si-Al and high loss on ignition (LOI). The highest contents of SiO_2 and Al_2O_3 are up to 57.76% and 16.56%, with the averages of 46.99% and 13.67%, respectively (Table 2).

4.2. Geochemical characteristics of trace elements of oil shale

The inductively coupled plasma-mass spectrometric (ICP-MS) analysis showed that the contents of Sr, Cs, Zn, Rb and Pb in oil shale samples were mostly higher than their average contents in the crust. The contents of Sr and Cs were significantly higher, the highest content of Sr in some samples was seven times that in the crust, while the highest content of Cs was 15 times that in the crust. Ba was somewhat abundant in few samples, the highest content of the element being 7.5 times its average content in the crust.

Table 2. Contents of major elements in oil shale from the Yin'e Basin

Sample No.	Relative content of elements, %											
	SiO_2	Na_2O	MgO	Al_2O_3	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	FeO	LOI
11-108	53.74	3.76	2.05	15.66	0.20	3.34	1.96	0.79	0.05	2.27	4.07	11.87
11-98	37.02	1.55	1.74	11.54	0.28	2.14	6.30	0.56	0.07	5.17	5.32	25.52
11-93	51.14	2.01	2.94	14.91	0.17	2.46	2.82	0.71	0.08	0.63	4.38	17.73
11-91	47.94	1.78	2.61	14.39	0.17	2.61	4.74	0.68	0.10	0.16	4.60	19.91
11-17	56.76	2.08	2.82	16.56	0.13	2.82	0.85	0.77	0.06	0.21	4.84	12.00
11-88	34.70	1.38	5.34	8.96	0.32	2.00	16.05	0.51	0.23	0.62	3.07	26.34
11-12	54.30	2.05	2.58	15.46	0.16	2.57	1.07	0.81	0.04	1.60	3.86	15.41
11-3	39.66	1.61	4.57	10.50	0.50	1.86	9.56	0.52	0.18	0.31	3.81	26.88
11-75	48.72	2.01	3.07	14.21	0.32	2.46	2.13	0.72	0.05	2.26	3.35	20.51
11-39	39.72	1.61	6.29	10.80	0.41	2.07	7.47	0.65	0.16	1.02	3.33	26.14
11-35	49.48	1.94	2.46	14.97	0.26	2.53	2.28	0.74	0.05	2.38	4.67	17.42
11-32	52.36	2.01	2.27	15.63	0.11	3.83	1.24	0.78	0.03	1.76	6.56	13.65
11-48	45.32	3.93	2.15	14.14	0.10	2.71	0.81	0.71	0.06	0.94	3.40	25.65
Average	46.99	2.13	3.15	13.67	0.24	2.57	4.41	0.69	0.09	1.49	4.25	19.93

4.3. Content characteristics of rare earth elements

A total of 12 oil shale samples were analyzed for rare earth elements (REE) content. The contents of REE were between 94.79×10^{-6} and 178.13×10^{-6}, with an average content of 126.17×10^{-6}, which is about 0.73 time those in North American Shale Composite (NASC). The total contents of light rare earth elements (ΣLREE) were from 70.15×10^{-6} to 128.59×10^{-6}, with an average content of 95.21×10^{-6}, i.e. about 0.60 time those in NASC. The total contents of heavy rare earth elements (ΣHREE) were between 24.64×10^{-6} and 49.55×10^{-6}, with an average content of 30.95×10^{-6}, being about 2.04 times those in NASC (Tables 3 and 4). A standardized analysis based on standard chondrite values showed that light rare earth elements (LREE) were abundant and heavy rare earth elements (HREE) were depleted in Bagemaode oil shale samples.

5. Quality characteristics of oil shale

For the resource potential evaluation of oil shale, parameters such as oil yield, content of semi-coke, ash and volatiles, and calorific value are important [9–12].

Table 3. REE contents in oil shale from the Yin'e Basin, ω(B) 10^{-6}

Sample No.	Oil yield, %	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
11-50	3.60	18.70	37.90	4.42	17.40	3.55	0.75	3.14	0.56	3.20	0.64	1.75	0.29	1.80	0.29	17.34
11-46	3.70	18.60	36.90	4.31	17.20	3.48	0.76	3.13	0.53	3.25	0.67	1.87	0.31	2.03	0.34	18.67
11-44	3.80	15.50	30.30	3.61	14.40	3.01	0.64	2.69	0.46	2.75	0.58	1.71	0.29	1.91	0.32	16.63
11-80	4.40	21.10	42.30	5.14	20.30	4.06	0.82	3.49	0.61	3.47	0.71	1.91	0.31	2.01	0.32	19.18
11-93	4.50	23.10	46.80	5.75	22.60	4.73	0.96	4.13	0.73	3.97	0.79	2.17	0.36	2.23	0.35	20.71
11-13	4.90	29.90	56.30	6.30	24.90	5.09	1.12	4.98	0.91	5.61	1.16	3.29	0.52	3.29	0.50	34.27
11-16	4.90	11.50	32.50	4.31	17.80	3.73	0.82	3.22	0.57	3.25	0.65	1.82	0.29	1.94	0.30	17.65
11-100	5.10	23.60	49.00	5.98	23.70	4.93	1.06	4.40	0.78	4.37	0.85	2.36	0.38	2.43	0.38	22.24
11-33	6.00	20.90	43.50	5.08	19.80	4.03	0.86	3.65	0.63	3.71	0.73	2.04	0.33	2.09	0.32	19.28
11-98	6.30	20.80	42.90	5.07	19.80	4.11	0.86	3.77	0.66	3.78	0.76	2.04	0.34	2.15	0.34	20.60
11-56	7.70	19.60	39.10	4.59	18.40	3.80	0.83	3.55	0.63	3.78	0.79	2.29	0.38	2.56	0.43	22.75
11-24	8.80	20.60	42.80	4.96	19.70	4.10	0.88	3.70	0.65	3.73	0.77	2.11	0.34	2.15	0.34	20.20
NASC		32.00	73.00	7.90	33.00	5.70	1.24	5.21	0.85	5.80	1.04	3.40	0.50	3.10	0.48	–
Chondrite		0.24	0.61	0.10	0.47	0.15	0.06	0.21	0.04	0.25	0.06	0.17	0.03	0.17	0.03	–

Table. 4. Geochemical parameters of REE in oil shale samples from the Yin'e Basin

Sample No.	ΣLREE	ΣHREE	ΣLREE/ΣHREE	ΣREE	(La/Yb) N	(La/Sm) N	(Gd/Yb) N	Ceanom
11-50	85.86	25.86	3.32	111.72	5.53	2.52	1.45	0.08
11-46	84.37	27.66	3.05	112.03	4.87	2.56	1.28	0.07
11-44	70.15	24.64	2.85	94.79	4.32	2.46	1.17	0.07
11-80	97.22	28.51	3.41	125.73	5.58	2.48	1.44	0.07
11-93	108.07	31.31	3.45	139.38	5.49	2.34	1.53	0.08
11-13	128.59	49.55	2.60	178.13	4.82	2.81	1.25	0.06
11-16	73.89	26.45	2.79	100.34	3.15	1.47	1.37	0.16
11-100	112.67	33.78	3.34	146.45	5.16	2.29	1.50	0.08
11-33	97.82	29.12	3.36	126.95	5.31	2.48	1.44	0.09
11-98	97.32	30.67	3.17	127.98	5.13	2.42	1.45	0.09
11-56	89.88	33.61	2.67	123.49	4.07	2.46	1.15	0.07
11-24	96.75	30.28	3.20	127.02	5.08	2.40	1.42	0.09

5.1. Oil yield and semi-coke content

The values of four parameters – oil yield, semi-coke content, water content and retorting gas yield, can be derived from oil shale retorting at low temperature [13]. A total of 308 samples were tested and analyzed for oil yield and semi-coke content.

Oil yield is the percentage amount of shale oil obtained from oil shale through retorting. According to oil yield, oil shale can be divided into high-oil-yield oil shale, with an oil yield higher than 10%; medium-oil-yield oil shale, with an oil yield of 5–10%; low-oil-yield oil shale, with an oil yield of 3.5–5%. The analysis results showed the maximum oil yield of oil shale samples to be 15.3%, with an average value of 4.72%. As can be seen from the cumulative oil yield probability distribution, the oil yield of the researched oil shale mainly ranges from 3.5 to 6%, which classifies it as oil shale with medium-low oil yield (Fig. 3a).

In Bagemaode oil shale samples the contents of semi-coke derived from low-temperature oil shale retorting were between 76.4 and 93.1%, with an average of 88.3%. The diagram of semi-coke distribution shows its content in the samples to range mostly from 86 to 92% (Fig. 3b).

(a)

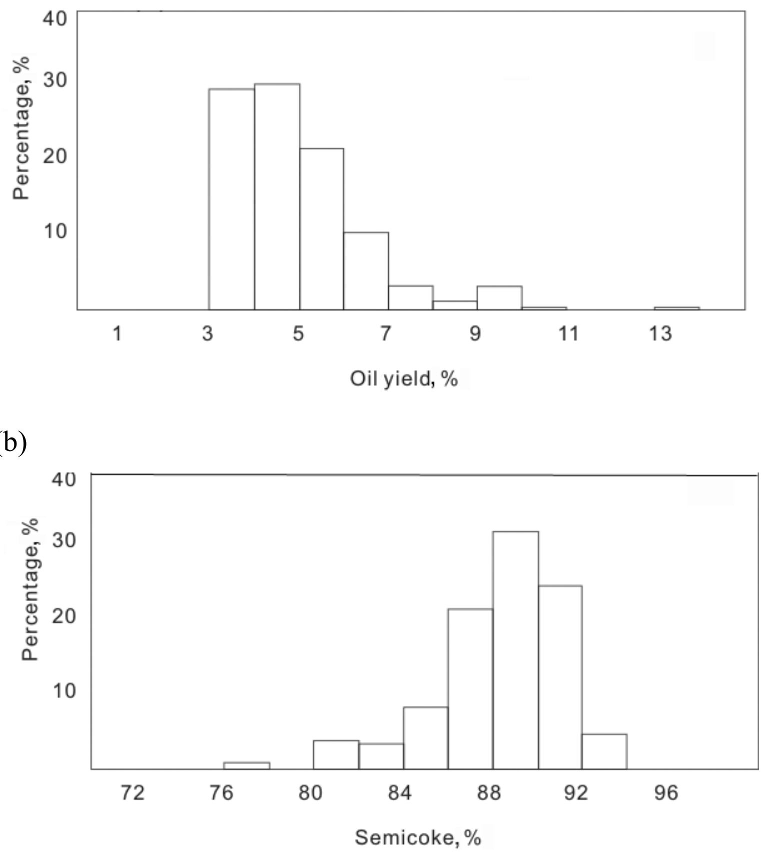

Fig. 3. Oil yield and semi-coke content of oil shale of the Yin'e Basin: (a) oil yield; (b) content of semi-coke.

5.2. Ash content

Ash content refers to the amount of residues remained in the sample after all combustibles therein have completely been combusted, and the minerals have undergone a series of complex chemical reactions like decomposition at a certain temperature.

A total of 268 oil shale samples were tested for ash content. The ash contents range from 63.13 to 88.45%, with an average value of 77.38%, mainly between 74 and 82%. According to Chinese grading standards on ash content, oil shale with the ash content between 66 and 83% is classified as high-ash oil shale. So, the Bagemaode oil shale belongs to oil shales with high ash content (Fig. 4a). The study showed the ash content and oil yield of the oil shale to be negatively correlated (Fig. 4b).

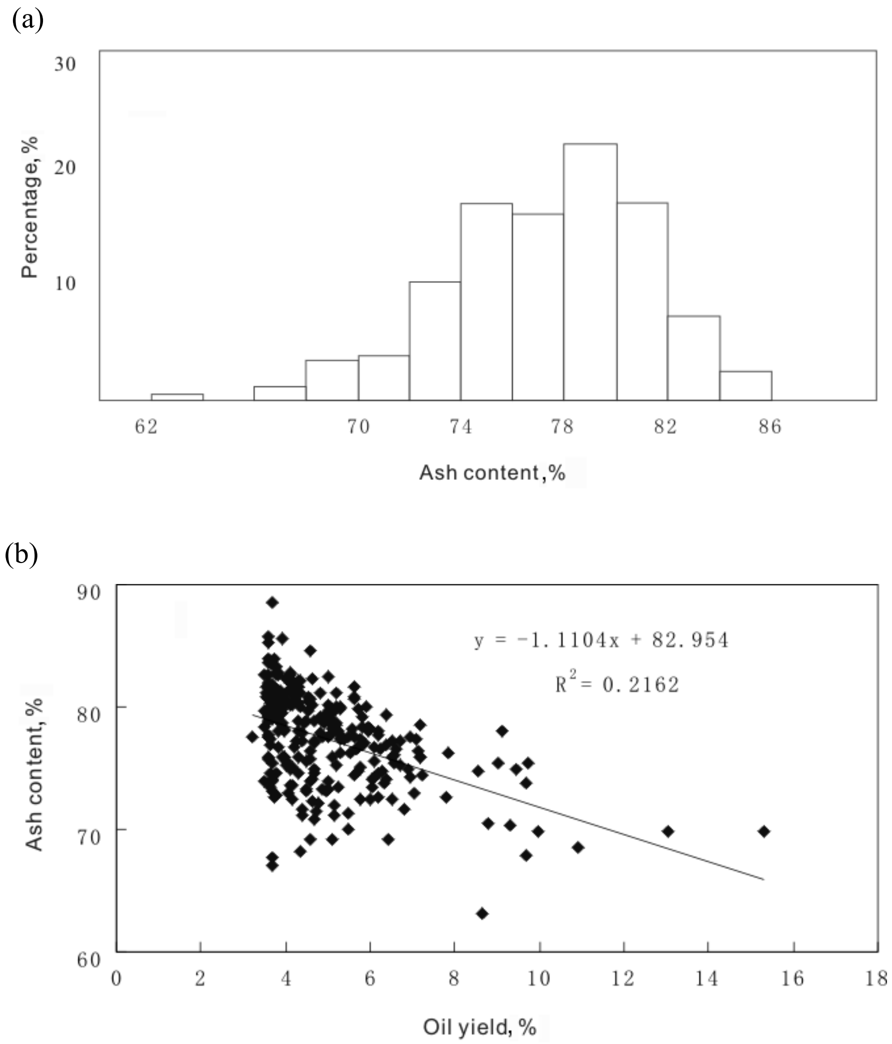

Fig. 4. Ash content and correlation with oil yield of oil shale of the Yin'e Basin: (a) ash content; (b) correlation between ash content and oil yield.

5.3. Volatiles content

Volatiles content is the amount percentage obtained by subtracting the water content percentage from the reduced weight percentage of the sample heated for some time in the absence of air at a certain temperature. The content of volatiles that come from organic components in the sample is an important indicator to characterize its organic matter. The analysis showed that the volatiles contents of the researched oil shale samples range from 11.97 to 23.12%, with an average content of 17.38%, mainly between 15 and 19% (Fig. 5a). There was established a positive correlation between the volatiles content and oil yield of Bagemaode oil shale, with a correlation coefficient of 0.32 (Fig. 5b).

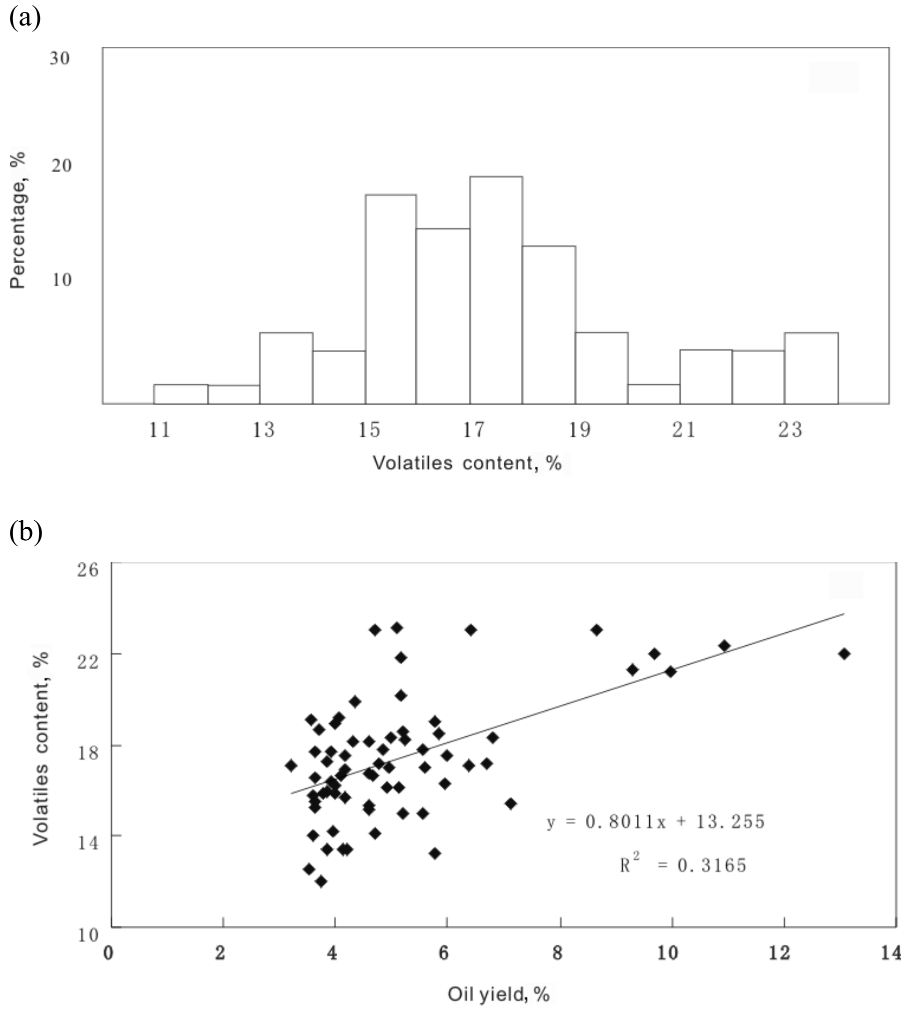

Fig. 5. Volatiles content and correlation with oil yield of oil shale of the Yin'e Basin: (a) volatiles content; (b) correlation between volatiles content and oil yield.

5.4. Calorific value

Calorific value means the amount of heat generated in the complete combustion of oil shale per unit weight. As oil shale can be used for retorting and as fuel for power generation, its calorific value is an important reference parameter.

A total of 124 oil shale samples were tested for calorific value. The data showed that the calorific values of samples were from 1.17 to 8.24 MJ/kg, with an average value of 3.82 MJ/kg, mainly between 3 and 6 MJ/kg. The studied oil shale belongs to oil shales with low calorific value (Fig. 6a). Oil shale with higher calorific value was developed in oil shale layers 2-1 and 2-2. The calorific value of oil shale is closely related to its oil yield and volatiles content. The regression analysis showed the correlation coefficient between calorific value and oil yield to be 0.46 (Fig. 6b).

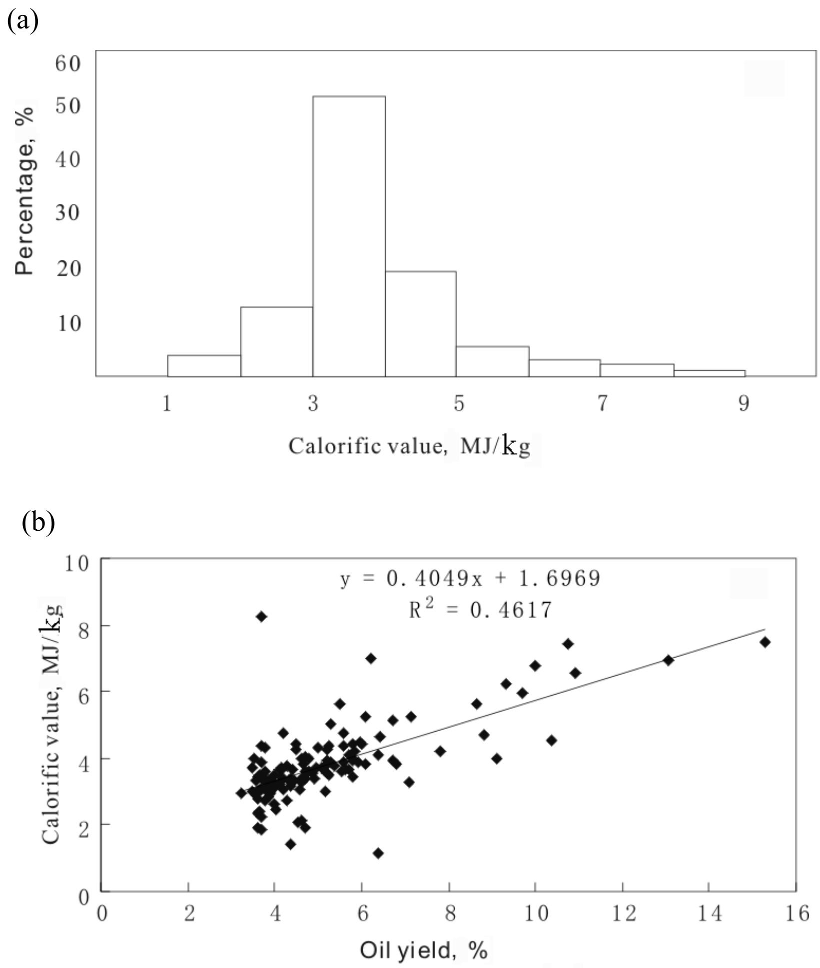

Fig. 6. Calorific value and correlation with oil yield of oil shale of the Yin'e Basin: (a) calorific value; (b) correlation between calorific value and oil yield.

6. Resources potential analysis of oil shale

6.1. Oil shale resources potential

A block method was used in the resource evaluation. Oil shale layers, oil yield, rock specific gravity and thickness were determined through the recognition of oil shale layer group. Taking oil shale layer group as the evaluation unit, and block and section as the basic computing unit, by using the volumetric method, the amount of oil shale/shale oil resource in each block and section was calculated, and the amounts of oil shale/shale oil resource in each oil shale layer group were summed up for the final prediction of a favorable area and estimation of its potential resources of oil shale [4].

The resources evaluation showed that the proved reserves of Bagemaode oil shale are 3.976 billion tons, of which oil shale with an oil yield higher than 3.5% and less than or equal to 5% accounts for 3.247 billion tons, and oil shale with an oil yield higher than 5% and less than or equal to 10% makes up 0.702 billion tons. Based on reserves statistics by buried depth, the proved reserves of oil shale with a buried depth of 0–50 m are 0.990 billion tons and those of oil shale with a buried depth of 50–100 m are 2.036 billion tons. The proved reserves of oil shale with a buried depth of 100–50 m are 0.862 billion tons, and those of oil shale with a buried depth of 150–200 m are 0.248 billion tons. In addition to the discovered resources, the predicted resources distributed in the two main deposits of the research area were estimated to be about 1.508 billion tons. So, the evaluation showed that the resources of Bagemaode oil shale are rich and, being buried at a shallow depth, they have a good development potential.

6.2. Comprehensive utilization potential of oil shale

Oil shale can be used for retorting and power generation, and the remaining semi-coke and ash can be further comprehensively utilized in the chemical and building materials industries and for extracting metals [14–16]. However, the development and utilization of oil shale is also faced with serious problems like environmental pollution and high development costs, especially the remaining ash would bring environmental problems like farmland occupation and groundwater pollution. Therefore, the efficiency of resources utilization shall be maximized for "extreme extraction" so as to achieve a clean and harmless oil shale industry.

6.2.1. Production of high-strength and energy-saving building ceramics

Liu et al. have obtained a patent "Porous Insulation Building Materials Produced by Oil Shale" [17] based on the richness of oil shale in clay minerals and organic matter. By using this patent technology, oil shale can be used to produce high-strength and energy-saving building ceramics. Taking full advantage of abundant clay minerals, combustibles uniformly distributed in oil shale like organic matter, as well as waste gas like CO, CO_2, H_2O released from its combustion to create pores, without leaving solid slag to occupy land, this technology is the most ingenious and comprehensive utilization of mineral resources. According to the patent, the content of quartz in oil shale should be less than 40% to reduce the sintering temperature of ceramics, the content of clay minerals should be higher than 20%, and that of organic matter should be higher than 6% (oil yield should be about 3.5%).

Analysis showed that the studied oil shale is also rich in clay minerals (average content 37%), the average content of quartz is 32%, while that of kaolinite is particularly high. As kaolinite is an important raw material for producing ceramic green bodies and clay refractories, this technology may be used to develop and utilize the low-oil-yield oil shale of the research area. The whole process is free from polluted emissions and waste residues to ensure a green environment.

6.2.2. Extraction of alumina and silica

Retorting and power generation are currently the most important applications of oil shale. Oil shale ash remaining from combustion takes up a lot of farmland area and pollutes underground water, which are major concerns the oil shale industry is facing. The contents of SiO_2 and Al_2O_3 in oil shale ash are very high. Therefore, some scholars proposed a technology by which alumina and silica can be extracted from oil shale ash. Not any form of SiO_2 in rock can be used to produce silica, it must be active silicon. Only the SiO_2 existing in clay minerals in rock is active [18, 19]. As is known from the X-ray diffraction analysis, oil shale is very rich in clay minerals, which is conducive to the production of silica. Usually in the production of alumina and silica, first, Al_2O_3 is produced, and then the remaining residues are used to produce silica through alkali treatment. As earlier experiments have shown, the contents of inorganic metals like $A1_2O_3$ and SiO_2 in oil shale ash should be more than 60%, to enable extraction of alumina and silica [9–23]. The chemical analysis of Bagemaode oil shale showed SiO_2 and Al_2O_3 to be its major oxides. By avoiding loss on ignition, the content of SiO_2 was up to 64.5%, with an average content of 58.4%; the content of Al_2O_3 was up to 19.02%, with an average content of 16.98% (Table 2). Therefore, the overall average percentage of SiO_2 and Al_2O_3 in the ash of Bagemaode oil shale may reach 75.38%, which is suitable for the extraction of alumina and silica.

6.2.3. Extraction of trace and rare earth elements

Some scientists have extracted metal elements like Ti, Fe, Cr, Mn and Ni, as well as rare earth elements (REE) from oil shale ash through a series of chemical separation, extraction and ion exchange procedures [24, 25]. Compared with their average contents in the crust, the abundances of metal trace elements like Sr, Cs, Zn, Rb, Pb and Co in the studied oil shale are relatively high. The highest content of Cs can be up to 15 times its average content in the crust. The Bagemaode oil shale is also rich in REE, their total content (ΣREE) being between 67.86×10^{-6} and 187.04×10^{-6}, with an average content of 132.91×10^{-6}, which is about 3 to 100 times that in chondrite. The abundance of light rare earth elements (LREE) is even more obvious. ΣLREE ranges from 61.56×10^{-6} to 167.47×10^{-6}, with an average of 118.48×10^{-6}, being about 27–74 times that in chondrite. At the same time, the combusted oil shale is generally more enriched in trace and rare earth elements. Therefore, these elements can be extracted from oil shale after it has been combusted for power generation purposes, which gives a significant economic benefit with higher added value. In short, the technology may contribute to solving environmental problems like farmland occupation by waste residues remained from oil shale combustion and processing, as well as groundwater pollution by poisonous metals in residues, to achieve a combination of environmental protection and economic benefits.

6.2.4. Other high value-added building materials

In addition to the extraction of alumina, silica, trace and rare earth elements, oil shale ash can also be used to produce ceramsite and low-clinker cement [26, 27]. Currently, the technology attempts to maximize the use of ash remaining from the low-temperature retorting of oil shale to turn the waste into treasure with high value-added economic benefits.

6.2.5. The flow of comprehensive development and utilization of oil shale

Based on the above comprehensive analysis of petrologic, petrogeochemical and quality characteristics, this article proposes that an appropriate program of development and utilization of Bagemaode oil shale should be prepared (Fig. 7). For oil shale with lower oil yield and lower calorific value, the program to be developed should foresee production of high-strength and energy-saving building ceramics, while the fire-resistant properties of kaolinite in oil shale as well as abundant pores produced through the combustion of organic matter could be fully made use of. To oil shale with lower oil yield and higher calorific value, the one-stop joint production of power-metals-silica-building materials can be applied. To oil shale with medium-high oil yield and lower calorific value, the one-stop joint process of retorting–production of metals-silica-building materials can be applied. The one-stop joint process of oil refining–power generation–metals-silica-building materials production can be applied to oil shale with medium to high calorific value. In this way, the most economical and effective method of multi-channel and multi-combination comprehensive development and utilization of Bagemaode oil shale can be achieved, taking into account its different characteristics.

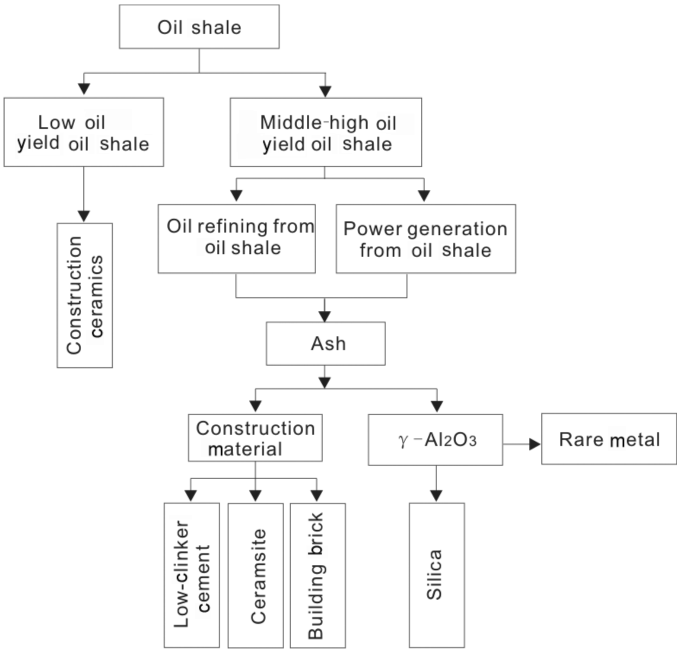

Fig. 7. Comprehensive utilization technological process of oil shale of the Yin'e Basin.

7. Conclusions

1. The Bagemaode oil shale is a mudstone-type oil shale. In addition to rich organic matter, it also contains detrital minerals like quartz and feldspars, as well as clay minerals like kaolinite, andreattite and illite, with the respective average content of 45% (detrital minerals) and 37% (clay minerals). Analysis of mineral abundances showed that the contents of SiO_2 and Al_2O_3 were higher, with an average content of 46.99% and 13.67%, respectively.
2. The oil shale in the research area is rich in trace and rare earth elements. Compared with their average contents in the crust, the abundances of Sr, Cs, Zn, Rb, Pb and Co in Bagemaode oil shale are relatively high. The total content of rare earth elements is between 67.86×10^{-6} and 187.04×10^{-6}, with an average content of 132.91×10^{-6}, i.e. about 3 to 100 times the content of rare earth elements in chondrite.
3. The maximum oil yield of Bagemaode oil shale is 15.30%, with an average oil yield of 4.72%; an average ash content of oil shale is 77.38% and average calorific value 3.82 MJ/kg. The oil shale is characterized by a low-medium oil yield, low calorific value and high ash content.
4. Resource evaluation showed that the Bagemaode oil shale has abundant proved reserves, 3.976 billion tons, which are characterized by a shallow burial depth. Based on the quality, petrologic and petrogeochemical

characteristics of oil shale, this article proposes a multi-channel and multi-combination comprehensive development model of oil refining–power generation–metals-silica-building materials production.

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