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Selection of favourable targets for the in-situ conversion of continental oil shale in China

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Abstract. *China has abundant oil shale resources and in-situ conversion is necessary for the large-scale, efficient and environmentally friendly development of this source rock. Despite the numerous researches carried out on in-situ transformation, reservoir reconstruction and heating technology, there is a lack of selection and evaluation criteria for high-quality mining areas. Therefore, it is urgent to perform geological evaluation and selection of favourable target areas for the in-situ conversion of oil shale-bearing areas in continental basins in China. In this paper, based on a wealth of research and previous studies, the geological characteristics of oil shale deposits in China's continental basins are studied. The in-situ conversion of oil shale mainly depends on the quality of rock, deposit characteristics, resource amount and hydrological conditions for site selection. On this basis, geological parameters, such as oil yield, organic matter type and maturity, ore body thickness, stratum dip angle, tectonics, lithology of the oil shale body roof and floor, oil shale resources and water content, are further considered. In addition, in conformity with the factor product method, the comprehensive geological parameters of each mining area are obtained and sorted according to a weighting coefficient. The preliminary results reveal that the Fushun and Bagemaode mining areas are two first-class favourable target areas. Gaozhou, Maoming, Fuyu-Changchun Ridge and eight other mining areas are second-class, less favourable target areas, while 16 future alternative areas include Tongchuan, Qidaoquanzi, Tanshanling, etc.*

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1. Introduction

China has abundant oil shale resources, with an annual output of oil less than 800,000 tons [1]. However, the development and utilization of these resources are limited to only some basins, such as Fushun, Junggar, Beipiao, Minhe and Dachanggou. Thus, in China, the exploitation of an important strategic supplementary energy source, oil shale, is far from being sufficient. The in-situ conversion offers wide prospects for the utilization of underground oil shale [2] and provides a good opportunity for its large-scale, efficient and environmentally friendly development in the country.

Since the 1950s, many countries have been actively engaged in the in-situ conversion of oil shale, mainly by heating the rock using various heating methods to promote the rapid pyrolysis of its organic matter to generate hydrocarbons and obtain oil [3–9]. In the in-situ conversion experiments, technologies such as blasting and fracturing have been used [4, 10]. At present, the in-situ conversion technology of oil shale is in the preliminary or pilot test stage, consisting mainly in heating the underground rock through physical and local chemical combustion technologies. The research is mainly focused on heating technology, reservoir transformation and hydrocarbon generation products [11–13]. Three companies have carried out in-situ oil shale conversion experiments using combustion heating technology. Namely, Sinclair Company has performed experiments in the Green River Basin of the United States, the Western Research Center has done the respective experiments in the United States, and Zhongcheng Company has conducted pilot tests in the southeast uplift of the Songliao Basin in China [3, 4, 6]. At the same time, there are many research groups that are developing and experimenting on physical heating technology and technical schemes. The most successful technologies are the Schell in-situ conversion process (Schell ICP), the Chevron crush technology, the AMSO (EGL) technology, the Petro Probe Mountain West Energy (MWE) in-situ vapor extraction (IVE) process, and the thermal convection technology developed by the Taiyuan University of Technology [3, 7, 8]. Such technologies mainly use underground heaters, heat-conducting materials or high-temperature gas to heat oil shale and promote hydrocarbon expulsion from it. Local chemical pyrolysis technology was mainly developed by Jilin University of China and Israel Asia Technology Co., Ltd. Its principle is to inject heated air into a local columnar microreaction unit, and when the thermal cracking of organic matter is gradually transferred outwards during the heating process, the hydrocarbon generation and expulsion range of oil shale slowly increases [5, 6]. The above in-situ oil shale conversion technologies have been tested both in the Green River Basin of the U.S., whose oil shale is of good quality and large thickness, and in the Songliao Basin of Northeast China, with oil shale of medium thickness and quality. So, considering the great number of oil shale deposits that would be suitable for in-situ conversion, it is urgent to carry out the geological evaluation of the process and select favourable target areas.

On applying the in-situ conversion technology for large-scale oil shale development, the primary task is to evaluate its resources available for the process and select suitable sites. Since this work has not been systematically carried out, it is very important to establish a relatively systematic geological parameter system for the in-situ conversion site selection of oil shale to provide normative guidance and a scientific basis for its evaluation and large-scale development. Based on the fundamental geological characteristics data on the key oil shale mining areas in China obtained by the authors during the two rounds of resource evaluation (Table 1), this paper proposes a preliminary set of geological evaluation parameters for the in-situ site selection of oil shale for the future.

2. Basic characteristics of oil shale in China

The first round of national oil shale resource evaluation in 2003–2006 showed that oil shale in China is mainly distributed in 47 basins and 80 mining areas. The oil shale resources are 719.9 billion tons, and synthetic oil shale can reach 47.6 billion tons [14]. Since 2006, many enterprises and institutions across China have invested much exploration work to identify and discover oil shale basins or ore-bearing areas in the Songliao Basin (Fuyu-Changchun, Qianguo Nong'an, Shenjingzi, Sanjingzi-Dalinzi), the northern foot of Bogda Mountain in the Junggar Basin (Wujiawan, Mutasi, Baiyanghe, Shichanggou, etc.), the Yin'e Basin in Inner Mongolia, and the Dachanggou Basin in Xinjiang (Shitanyao and Hulanbastao). The exploration degree of oil shale has been obviously improved, which also shows that China's oil shale resources are large. With appropriate development technology, it will certainly become an important supplementary and strategic energy source for the country.

The national oil shale resource evaluation in 2003–2006 shows that there are three main types of oil shale deposits in China. The first type includes deposits of medium-thickness and -quality oil shale. The deposits are widely and stably distributed. The top and bottom plates are dark mudstone. The average oil yield of oil shale is approximately 5% and the average cumulative thickness is mostly 20 m. The type of organic matter is mainly sapropel. This type of deposit is primarily developed in the Songliao Basin, the Ordos Basin and other large basins [15, 16]. The second type includes thick high-quality oil shale. The distribution of oil shale is relatively stable. The roof and floor are also dominated by dark mudstone. The average oil yield is more than 8%, the cumulative thickness can reach hundreds of metres and the type of organic

Table 1. Basic characteristics of geological parameters of large and medium oil shale deposits

Basin	Ore-bearing area	Depth, m	Oil content, wt%		Main kerogen types	Maturity of organic matter
			Highest	Average		
Songliao	Fushun-Changchunling	38–926	11.1	4.8	I–II_1	Immature–low-mature
	Qianguo-Nongan	6–547	10.5	4.49	I–II_1	Immature–low-mature
	Shenjingzi	34–924	7.2	4.63	I–II_1	Immature–low-mature
	Sanjingzi-Dalinzi	108–642	9.8	4.37	I–II_1	Immature–low-mature
Luozigou	Luozigou	0–800	14.4	6.7	II_1	Immature
Huadian	Huadian	0–1000	24.8	8.6	I–II_1	Immature
Meihe	Meihe	0–1000	11.4	5.3	II_1	Immature
Yilanyitong	Dalianhe	0–1000	9.1	6.2	II_1	Immature
Fushun	Fushun	0–750	12.6	7.0	I–II_1	Immature
Heishan	Fuxinyemataohai	14–400	5.1	4.8	II	Immature–low-mature
Beipiao	Daqingshan	0–420	11.9	5.2	I–II_1	Immature–low-mature
Chaoyang	Qidaoquanzi	20–500	7.0	4.8	II_1	Immature–low-mature
Jianchang	Jianchang	10–300	4.2	4.0	II_1	Immature–low-mature
	Lingyuan	0–500	5.6	4.3	II_1	Immature–low-mature
Bohai Bay	Changlewutu	200–850	17.3	8.4	II_2	Immature–low-mature
Jiaolai	Zhoujiayingzi	100–560	12.2	8.1	II_1	Immature
	Huangxian	60–100	29.8	13.6	II_1	Immature
Tongbai	Wucheng	20–300	8.7	6.2	II	Immature–low-mature
Ordos	Binxian	0–1000	13.7	6.3	I–II_1	Immature–low-mature
	Chunhua	0–450	7.8	5.3	I–II_1	Immature–low-mature
	Tongchuan	0–250	9.3	6.5	I–II_1	Immature–low-mature
Dachanggou	Shitanyaobei	0–300	15.6	6.5	II_1–II_2	Immature–low-mature
	Hulanbasitao	110–280	12.4	8.7	II_1–II_2	Immature–low-mature
Qaidam	Yuka	0–1000	11.4	6.5	II_1	Immature–low-mature
Dzungaria	Yaomoshan	0–590	22.6	7.0	I–II_1	Immature–mature
	Lucaogou	0–500	12.7	7.1	I–II_1	Immature–mature
	Mutasi	0–373	24.0	5.9	I–II_1	Immature–mature
	Wujiawan	0–1000	22.3	6.1	I–II_1	Immature–mature
	Shichanggou	0–1000	20.0	7.1	I–II_1	Immature–mature
	Shanghuangshanjie-Panjiakouzi	0–1000	18.9	6.2	I–II_1	Immature–mature
Minhe	Yaojie	0–1000	17.7	5.6	I–II_1	Immature–low-mature
	Haishiwan	340–910	6.9	4.7	I–II_1	Immature–low-mature
	Tanshanling	0–1000	15.6	6.1	I–II_1	Immature–low-mature
Yine	Bagemaodekuang	0–300	10.6	7.0	I–II_1	Immature–low-mature
Beibuwan	Danzhou	0–500	18.4	7.2	I–II_1	Immature
Maoming	Dianbai	0–850	13.0	6.5	II_1	Immature–low-mature
	Gaozhou	0–850	6.3	5.6	II_1	Immature–low-mature
	Maoming	0–722	11.1	6.5	II_1	Immature–low-mature

Note: The Lunpola and Qiangtang basins are located in the ecologically fragile areas of Tibet in China. As the eco-environmental effects of in-situ oil shale conversion have not been systematically studied, the oil shale of these two basins has not been considered in this paper.

Table 1 (continued)

Thickness, m		Dip angle of stratum, °	Structural complexity	Lithology of roof and floor of ore bed	Resources, 100 million tons	Resource abundance, 10^4 t/km^2
Maximum single layer	Cumulative					
7.8	38.8	1–6	Simple	Mudstone	445.1	3901.5
12.0	16.6	1–5	Simple	Mudstone	311.7	1252.7
10	34.5	2–6	Simple	Mudstone	148.9	1611.7
5.8	24.0	1–4	Simple	Mudstone	123.2	1076.0
6	49.9	4–6	Simple	Sandstone	9.5	7729.9
3.8	32.7	15–20	Simple	Sandstone	15.2	4546.8
5.2	20.0	15–20	Moderate	Mudstone	8.8	7665.5
2.5	6.1	11–17	Simple	Thin layer of coal or sandstone	9.6	1220.4
191.0	195.5	15–44	Simple	Mudstone	36.7	10294.5
2.5	10.1	20–40	Moderate	Sandstone	3.2	5850.1
23.4	150.3	4–12	Simple	Mudstone	14.0	4263.9
13	25.0	10–20	Simple	Mudstone	72.7	4760.1
9.8	22.1	10–14	Simple	Mudstone	6.7	2781.6
7.8	25.7	10–15	Simple	Mudstone	23.4	2513.3
16.0	46.1	5–20	Simple	Mudstone	4.2	7879.9
2.8	16.2	10–30	Moderate	Thin layer of coal or mudstone	3.1	3433.0
17.8	30.0	3–20	Moderate	Thin layer of coal or mudstone	7.6	1013.3
3.0	33.0	5–24	Moderate	Sandstone	3.9	7014.4
4.3	6.88	3–6	Simple	Mudstone	5.1	1606.1
3.5	9.73	3–15	Simple	Mudstone	2.9	2312.6
10.6	24.3	3–15	Simple	Mudstone	9.3	2651.1
17.8	30.5	4–6	Simple	Mudstone	5.1	3682.3
7.4	15.0	1–3	Simple	Mudstone	4.7	1645.1
14.0	25.0	35–70	Complex	Mudstone	43.5	991
31.6	53.3	50–70	Complex	Mudstone	2.7	11688.3
18.4	66.2	60–80	Complex	Mudstone	9.7	36882.1
33.9	80.0	50–60	Complex	Mudstone	2.1	6907.9
74.0	106.8	50–60	Complex	Mudstone	7.5	5266.9
68.2	121.0	50–60	Complex	Mudstone	2.2	12087.9
56.8	145.1	60–70	Complex	Mudstone	26.1	35127.9
17.4	18.6	5–48	Moderate	Mudstone	4.4	2093.2
9.25	20.1	5–25	Simple	Mudstone	7.8	622.7
34.5	39.0	11–26	Simple	Mudstone	13.8	3472.6
18.0	35.4	4–10	Simple	Mudstone	28.3	5139.8
12.9	52.9	1–5	Simple	Thin layer or mudstone	27.5	6908.7
15.6	16.3	4–12	Simple	Mudstone	25.7	2893.8
20.0	24.7	3–7	Simple	Mudstone	26.5	4344.3
20.0	22.4	4–8	Simple	Mudstone	15.8	4230.3

matter is mainly sapropel, the Fushun Basin and the Junggar Basin being the most typical representatives of this type of deposit [1, 14, 17]. The third type comprises deposits of thin-layer high-quality oil shale. The distribution of oil shale is relatively limited and unstable. The roof and floor are mostly sandstone and coal seams. The average oil yield can be as high as 10%. The single-layer oil shale has a thickness ranging from 1 to 3 m. The cumulative thickness varies greatly. The types of organic matter are mainly humic sapropel and sapropelic humus. This type of oil shale is the most typical in basins such as Huadian and Huangxian [16, 18].

3. Parameter system for site selection evaluation of in-situ oil shale development

Judged by their basic characteristics, not all oil shale deposits in China are suitable for in-situ conversion [19, 20]. In the past, the geological evaluation of oil shale development mainly considered burial depth, thickness and oil yield, while the former was used as the main index for the selection of the development zone [21, 22]. The in-situ oil shale conversion technology uses the underground ore layer as “oil refinery”, and the geological factors regarded are far more numerous [23]. After decades of exploration, some scholars have concluded that geological factors, such as oil yield, thickness, burial depth, minerals and formation pressure of oil shale, all affect the in-situ conversion of the rock [24–28]. Proceeding from the results of previous studies coupled with those of the in-situ oil shale conversion site selection work carried out by the authors in the Songliao Basin in recent years, this paper expounds on the geological evaluation of the pertinent selection based on four aspects, namely, oil shale quality, ore layer and resources characteristics, and hydrological conditions. In addition, a preliminary relevant parameter system is presented. The geological evaluation parameters are quantitatively characterized through weight coefficients, so, the higher the weight, the better the geological parameters. The weight coefficients are calculated using the following formula:

$$\delta = \frac{\alpha}{n},$$

where δ is the weight coefficient, n is the number of geological evaluation parameters, and α is the evaluation index of geological parameters, i.e., the better the geological parameters, the closer the evaluation index is to n, and, the worse the geological parameters, the closer the evaluation index is to 1.

3.1. Oil shale quality

The quality parameters of oil shale generally include oil yield, organic matter type, maturity and sulfur content [29]. Among them, the oil yield is the primary parameter that determines the economic significance of in-situ conversion [30]. In resource evaluation, oil shale is divided into three grades, according to oil yield: high-quality (oil yield > 10%), medium-quality (5% < oil yield ≤ 10%) and poor-quality (3.5% < oil yield ≤ 5%) [14]. At present, the weighted oil yield of oil shale in the in-situ conversion test target in the Songliao Basin is approximately 5%. Therefore, the layer of oil shale with an oil yield higher than 5% can be preliminarily considered as a layer for in-situ conversion. Furthermore, weight coefficients are given to oil shales of different qualities: high-quality oil shale is denoted by 1, medium-quality oil shale, by 0.66–1, and poor-quality oil shale, by 0.33–0.66. For medium- and poor-quality oil shales, the specific weight coefficient is obtained by linear interpolation within the weight coefficient interval according to the specific oil yield.

The type of kerogen determines the hydrocarbon-generating capacity of organic matter. Sapropelic organic matter easily generates oil, humic organic matter tends to generate gas, while the oil and gas generating capacity of mixed organic matter is between those of the above two types of organic matter [31]. Considering that the in-situ conversion of oil shale aims primarily to obtain oil, sapropelic oil shale should be most suited for this purpose, followed by humic sapropelic oil shale, while sapropelic humic oil shale is of poor oil-generating capacity. The weight coefficients of sapropelic, humic and humic sapropelic oil shales are respectively 1, 0.66 and 0.33.

The maturity of organic matter determines its residual hydrocarbon generation potential in oil shale. The lower the maturity, the greater the residual hydrocarbon generation potential of organic matter. Chinese oil shale is basically in the immature–low-mature stage, and only the oil shale in the Junggar Basin is in the low-mature–mature stage [17]. The weight coefficients of these oil shales are set as 1 and 0.5.

The sulfur content is a significant parameter for oil shale development; however, it may cause environmental problems. Numerous data tests show oil shale in China to be mainly ultralow-sulfur and low-sulfur, whose weight coefficient is basically 1.

3.2. Ore layer characteristics

The characteristic geological parameters of the ore layer mainly include ore layer thickness, distribution area, stratum dip angle, structure, burial depth, the lithology of the roof and floor of the ore body, the physical properties of the ore bed and composition of rocks and minerals [19, 20].

In-situ conversion requires oil shale to have a certain single-layer thickness [17]. At present, the thickness of the in-situ target oil shale in the Songliao Basin is approximately 5 m, while the convective heating technology of

Massachusetts Institute of Technology (MIT) requires that the minimum thickness of oil shale should be 1 m. Since oil shale in China is mainly of medium quality, the thickness of the single-layer oil shale should be appropriately increased. In this paper, the thickness of the single-layer oil shale of 2 m is initially used as the minimum value, 2–5 m is used for the thinner ore layer, 5–10 m is used for the medium ore layer, and > 10 m is used for the thick ore layer. The weight coefficients are 0.33–0.66, 0.66–1 and 1, respectively. For thin and medium-thickness oil shale, the specific weight coefficient is obtained by linear interpolation within the weight coefficient interval according to its specific single-layer thickness.

The ore layer that is suitable for the in-situ conversion of oil shale is stably distributed, and the larger the area, the better. Moreover, oil shale resources are the product of the distribution area, thickness and density. Except for some basins, the thickness of most oil shales is almost the same (Table 1). Therefore, the distribution area and oil shale resources can be considered as one parameter, which are not discussed here.

The formation dip angle affects the hydraulic fracturing of oil shale deposits. Generally, this angle is too large for fracturing. According to the selection of the formation dip angle of the shale gas fracturing horizon, the formation dip angle smaller than 10° is classified as an angle of high-quality interval, an angle between 10° and 30° is of medium-quality interval, and an angle larger than 30° is of poor-quality interval. As the hydraulic fracturing processes of oil shale and shale gas are basically similar, this paper uses the classification and annotation of the shale gas formation dip angle for reference and gives weight coefficients of 1, 0.66 and 0.33, respectively.

The complexity of the formation structure not only affects the outcrop development of oil shale but also plays an important role in its in-situ conversion. Usually, the in-situ oil shale conversion target layer is a layer with a stable distribution and no large faults, the weight coefficient being 1 [7]. In case of a few faults, the weight coefficient of the layer with a more complex geological structure is 0.5. It is not recommended to select an ore bed with a large fault and complex geological structure, with the weight coefficient of 0.

The burial depth of oil shale has a great effect on outcrop development and in-situ conversion. The deeply buried oil shale has a strong diagenesis, which easily makes holes by hydraulic fracturing and maintains pore permeability channels in the later stage, but the development cost is high. The burial depth of oil shale is small, the water content of the formation is too high and diagenesis weak, which is not conducive to the maintenance of hydraulic fracturing and heating channels. Therefore, this parameter can be assigned only after the pilot test of in-situ oil shale conversion. At this stage when the burial depth of oil shale is approximately 300–600 m, it is recommended to carry out in-situ conversion.

The lithology of the roof and floor of the ore bed plays an important role in the in-situ heating of oil shale. The roof and floor of oil shale are thick dense mudstone or marl, which effectively prevent the diffusion of heat flow to the nontarget layer. If the roof and floor of oil shale are sandstone, it leads to a large loss of heating fluid or energy, which is not conducive to the high-temperature heating of the ore layer. Therefore, at this stage, the lithology of the roof and floor of the ore bed plays a rejection role in the in-situ conversion of oil shale. Now, the top and bottom plates of the ore layer of the oil shale ore layer are thick (generally greater than 5 m) mudstone, limestone or coal and other fine-grained dense sediments with a weight coefficient of 1. The roof and floor of the ore bed are thin (5–2 m) fine-grained dense sediments, the weight coefficient being preliminarily determined to be 0.5. In case the ore bed roof and floor are sandstone or extremely thin fine-grained dense sediments, the weight coefficient is determined to be 0.

Oil shale is a dense fine-grained organic-rich sedimentary rock that is part of ultralow-porosity and -permeability or even nonpermeable reservoirs [17]. Therefore, hydraulic fracturing and reservoir reconstruction are required to extract oil or gas from it. In the preliminary laboratory test, the researchers of the current paper discovered that after oil shale had been heated at high temperature (generally higher than 450 °C), the effect produced was similar to that generated after firing the clay. The hardness and brittleness of oil shale were significantly increased and the resulting cracks and pores could be effectively maintained. Therefore, the authors believe that the physical properties of the unheated oil shale bed have a little influence on the in-situ conversion of oil shale, which requires no assignment of weight coefficients.

In addition, Chinese oil shale has a high content of clay mineral, usually with high water sensitivity. However, the high-quality oil shale in some basins contains a large amount of calcite or dolomite, which is conducive to reservoir reconstruction, because the thickness of this type of oil shale is small and therefore it is not widely developed. Thus, the research group is of the opinion that the rock mineral composition has a relatively low influence on the selection of in-situ oil shale targets; hence, no weight assignment is made.

3.3. Oil shale resources abundance and availability for in-situ conversion

To date, oil shale resources available for in-situ conversion have not been evaluated, at the same time, basins and oil shale deposits have a certain positive correlation with the respective resources. For example, the Songliao and Ordos basins have massive oil shale resources, and oil shale horizons for in-situ conversion are widely developed. However, small deposits, such as the Huadian and Laoheishan basins, are hardly suitable for the in-situ conversion of oil shale. At the same time, large-scale development or resource depletion of oil shale deposits is not acceptable for in-situ conversion. According to the standard for solid mineral resources/reserves, this paper lists large-scale (the total amount of the remaining identified resources and potential resources is more than 2 billion tons) and medium-scale (the resource amount is 200 million tons to 2 billion tons) oil shale deposits as the mining areas for the in-situ oil shale conversion pilot tests. The weight coefficients of the above oil shale deposits are 1 and 0.5, respectively. Furthermore, for medium-scale oil shale deposits, the specific weight coefficients are obtained by linear interpolation within the weight coefficient interval according to their specific resources.

Resource abundance reflects the enrichment degree of oil shale resources per unit area. The small ground area and high resource abundance are ideal targets for in-situ conversion. The oil shale resources in the Songliao Basin and the Ordos Basin are very large, but their oil shale distribution area is also large and resource abundance is relatively small. Hence, this area is not favourable for the in-situ oil shale conversion on a large scale. Although the oil shale resources in the Fushun Basin, the Beipiao Basin and other basins are relatively small, their rock distribution area is smaller and resource abundance is higher. According to the classification of oil and gas resource abundance and based on the 5% oil yield standard, the oil shale resources scale is divided into three levels. The Level I oil shale deposit resource abundance is larger than 6000×10^4 t/km^2, that of Level II deposits is 1000 to 6000×10^4 t/km^2 and that of Level III deposits is smaller than 1000×10^4 t/km^2. The weight coefficients are 0.66 to 1 and 0.33 to 0.66, respectively. For Level II and Level III oil shales, the specific weight coefficient is obtained by linear interpolation within the weight coefficient interval according to the specific resource abundance.

3.4. Hydrological characteristics

The water content of the ore layer and the hydrogeological characteristics of the ore-bearing strata have an important impact on the heating of oil shale. The content of water in oil shale is too high or close to that in the underground water layer, as a result of which much energy is consumed during the heating process. Hence, it is impossible to heat oil shale at high temperatures. This shows that the ore layer with a high water content needs to be dewatered and blocked. Thus, the weight of the deposit with a low water content and simple hydrogeological conditions is set as 1, and the weight of the deposit with a high water content and complex hydrogeological conditions is set as 0.5. However, in practice, the hydrogeological conditions of different layers of the same deposit differ, so it is difficult to evaluate the deposit as a unified whole, and different specific analyses are required for this purpose.

4. Geological parameter weight of the favourable target area for the in-situ conversion of continental oil shale in China

In general, methods for optimizing the weight of evaluation parameters of the favourable target area for the development of oil shale ground retorting include the comprehensive index evaluation method, the expert assignment method, the two-factor method and the analytic hierarchy process. Among these methods, the comprehensive index evaluation method represents the average sum of the factors restricting the development and utilization of resources, which is simple to operate but not practical in the case of one rejection. The expert assignment method involves much subjectivity, while the two-factor method and the analytic hierarchy process are relatively complex and scientific and correspondingly weaken the influence of excellent and poor factors. In fact, in the in-situ conversion process of oil shale, excellent or poor factors often play a certain decisive role in its development. For example, the top and bottom plates of the combined oil shale rock are all sandstone, which makes the in-situ conversion basically impossible. At the same time, oil shale with excellent quality and relatively thin thickness may also become the object of priority for development. Therefore, the factor product method is used to calculate the weight of comprehensive geological parameters for the selection of favourable target areas for the in-situ conversion of continental oil shale in China. This method is not only simple to operate but also highlights the decisive role of special factors in the development process.

Since small oil shale deposits have no prospects for in-situ conversion, the authors optimized the favourable target areas for this process in 38 large and medium-sized ore-bearing areas in 20 continental oil shale basins in China, based on the above preliminary main parameters and corresponding weights. By this, the Tibet region, which is an ecological area, and the large and medium-sized Sichuan and Dayangshu deposits, whose maximum single-layer oil shale thickness is less than 1 m, were not considered. Furthermore, the organic matter type and formation dip angle may comprise two weight intervals. This simplified treatment adopts the average value of the sum of the weight coefficients of the corresponding intervals. Finally, the total score is obtained by multiplying the coefficients of various geological parameters and queueing these coefficients to provide suggestions for the selection of favourable target areas for in-situ oil shale conversion.

Based on data available in Table 1, high-quality oil shale layers are present in all basins, whereas their average oil contents may differ. For example, oil shale in the Huangxian mining area of the Jiaolai Basin is mainly of high quality, that in the Songliao Basin, which is undergoing in-situ pilot production, is generally of poor quality, and oil shale in other basins is mostly of medium quality. Oil shale with a single layer thickness of more than 10 metres is present in 22 ore-bearing areas, such as the Fushun and Maoming basins, while in some ore-bearing areas its cumulative thickness may reach

Table 2. Weight of geological parameters of large and medium oil shale deposits and optimization of favourable targets for in situ exploitation

Basin/Mining area	Oil content, wt%	Type of organic matter	Maturity	Thickness	Dip angle of stratum, °
Fushun	0.79	0.83	1.00	1.00	1.00
Bagemaodekuang	0.79	0.83	1.00	1.00	1.00
Gaozhou	0.70	0.66	1.00	1.00	1.00
Maoming	0.76	0.66	1.00	1.00	1.00
Fushun-Changchunling	0.62	0.83	1.00	0.84	1.00
Daqingshan	0.67	0.83	1.00	1.00	0.83
Shenjingzi	0.58	0.83	1.00	1.00	1.00
Danzhou	0.81	0.83	1.00	1.00	1.00
Dianbai	0.76	0.66	1.00	1.00	0.83
Qianguo-Nongan	0.55	0.83	1.00	1.00	1.00
Tongchuan	0.76	0.83	1.00	1.00	0.83
Qidaoquanzi	0.62	0.66	1.00	1.00	0.66
Tanshanling	0.73	0.83	1.00	1.00	0.50
Sanjingzi-Dalinzi	0.52	0.83	1.00	0.71	1.00
Shitanyaobei	0.76	0.5	1.00	1.00	1.00
Hulanbasitao	0.90	0.5	1.00	0.82	1.00
Binxian	0.75	0.83	1.00	0.58	1.00
Lingyuan	0.51	0.66	1.00	0.84	0.66
Changlewutu	0.88	0.33	1.00	1.00	0.83
Haishiwan	0.59	0.83	1.00	0.94	0.67
Jianchang	0.44	0.66	1.00	0.98	0.66
Chunhua	0.68	0.83	1.00	0.50	0.83
Yaojie	0.70	0.83	1.00	1.00	0.67
Huangxian	1.00	0.66	1.00	1.00	0.83
Meihe	0.68	0.66	1.00	0.67	0.50
Zhoujiayingzi	0.86	0.66	1.00	0.42	0.50
Yuka	0.76	0.66	1.00	1.00	0.00
Dafenhe	0.74	0.66	1.00	0.39	0.66
Huadian	0.90	0.83	1.00	0.53	0.50
Wujiawan	0.73	0.83	0.50	1.00	0.00
Fuxinyemataohai	0.62	0.5	1.00	0.39	0.33
Mutasi	0.72	0.83	0.50	1.00	0.00
Wucheng	0.74	0.5	1.00	0.44	0.67
Luozigou	0.77	0.66	1.00	0.73	1.00
Yaomoshan	0.79	0.83	0.50	1.00	0.00
Shichanggou	0.80	0.83	0.50	1.00	0.00
Shanghuangshanjie Panjiakouzi	0.74	0.83	0.50	1.00	0.00
Lucaogou	0.80	0.83	0.50	1.00	0.00

Note: The thickness of a single layer of oil shale in the Fushun Basin can reach hundreds of meters, so the formation dip angle can be ignored for the in-situ conversion of oil shale, thus the value is assigned as 1.

Table 2 (continued)

Structural complexity	Lithology of roof and floor	Resources, 100 million tons	Resource abundance, 10^4 t/km^2	Overall weight coefficient	Ranking
1.00	1.00	1.00	1.00	0.66	1
1.00	1.00	1.00	0.93	0.61	2
1.00	1.00	1.00	0.88	0.41	3
1.00	1.00	0.88	0.87	0.39	4
1.00	1.00	1.00	0.85	0.37	5
1.00	1.00	0.83	0.88	0.34	6
1.00	1.00	1.00	0.70	0.34	7
1.00	0.50	1.00	1.00	0.33	8
1.00	1.00	1.00	0.78	0.33	9
1.00	1.00	1.00	0.68	0.31	10
1.00	1.00	0.70	0.77	0.28	11
1.00	1.00	1.00	0.91	0.24	12
1.00	1.00	0.83	0.82	0.21	13
1.00	1.00	1.00	0.67	0.21	14
1.00	1.00	0.59	0.84	0.19	15
1.00	1.00	0.58	0.70	0.15	16
1.00	1.00	0.59	0.70	0.15	17
1.00	1.00	1.00	0.76	0.14	18
1.00	1.00	0.56	1.00	0.14	19
1.00	1.00	0.66	0.54	0.11	20
1.00	1.00	0.63	0.78	0.09	21
1.00	1.00	0.53	0.75	0.09	22
0.50	1.00	0.57	0.73	0.08	23
0.50	0.50	0.66	0.66	0.06	24
0.50	1.00	0.69	1.00	0.05	25
0.50	0.50	0.53	0.82	0.01	26
0.00	1.00	1.00	0.66	0.00	Not recommended
1.00	0.00	0.71	0.67	0.00	Not recommended
1.00	0.00	0.87	0.89	0.00	Not recommended
0.00	1.00	0.65	0.94	0.00	Not recommended
0.50	0.00	0.53	0.98	0.00	Not recommended
0.00	1.00	0.50	1.00	0.00	Not recommended
0.50	0.00	0.55	1.00	0.00	Not recommended
1.00	0.00	0.71	1.00	0.00	Not recommended
0.00	1.00	0.52	1.00	0.00	Not recommended
0.00	1.00	0.51	1.00	0.00	Not recommended
0.00	1.00	1.00	1.00	0.00	Not recommended
0.00	1.00	0.71	1.00	0.00	Not recommended

hundreds of metres (Table 1). The oil shale organic matter in most mining areas is mainly type I–II1, and only its minor amount in some basins is type II2 (Table 1). This organic matter is basically in the low-mature to immature stage. Except for the Junggar and Qaidam basins, whose structure is complex and dip angle large, oil shale deposits in other basins have a dip angle smaller than 30° and a relatively simple structure (Table 1). Moreover, only the top and floor of oil shale formations in the Huadian, Luozigou and Tongbai basins are sandstone, while the rest are mudstone or coal seam deposits, which have good sealing conditions (Table 1).

Based on geological parameters, each basin is assigned the weight (Table 2). The oil shale deposits in the Huadian, Luozigou and Tongbai basins lack necessary plugging conditions for in-situ conversion due to the small thickness of a single oil-shale layer and the presence of sandstone on the top and bottom plates (Table 2). The weight of the geological parameters of the top and bottom plates of the ore layer is set as 0. The oil shale deposits in the Qaidam and Junggar basins have a complex structure and a large stratigraphic dip angle, so, they are not fit for in-situ conversion. The weight of the geological parameters of the stratigraphic dip angle and structural complexity is set as 0. The remaining 26 oil shale deposits in the mining area have overall weight coefficients. The Fushun Basin, with a weight coefficient of 0.66, is the most suitable depression for in-situ oil shale conversion in China. In the initial stage of selection, the first-class favourable target area for in-situ conversion is assigned a weight coefficient greater than 0.5, the second-class area is assigned a weight coefficient of 0.3–0.5, and the alternative area is given a weight coefficient smaller than 0.3. Among the oil shale basins evaluated in China, Fushun and Bagemaode are the first-class favourable target areas; Gaozhou, Maoming, Fuyu-Changchunling, Daqingshan, Shenjingzi, Danzhou, Dianbai and Qianguo Nongan are the second-class favourable target areas, and Tongchuan, Qidaoquanzi, Tanshanling and 16 other ore-bearing areas are future alternative areas.

The above suggestions made by the research group on the basis of the existing data are only preliminary. Considerable geological work is needed to select in-situ oil shale conversion target areas. With improving technology and geological exploration, the number of mining areas and resources that can be used for in situ oil shale conversion in China will continue to increase.

5. Conclusions

Oil shale quality, and ore layer, resources and hydrological characteristics are the key geological evaluation parameters for the selection of favourable target areas for in-situ oil shale conversion. These parameters can be further divided into geological parameters, such as oil yield, organic matter type and maturity, single ore layer thickness, formation dip angle, structure, roof and floor rock properties of the ore layer, oil shale resources characteristics, resource abundance and water content. Each geological parameter corresponds to a weight coefficient (0–1), and the factor product method is used to obtain the comprehensive parameter weight of each ore-bearing area.

Based on the difference in in-situ conversion geological parameters, the Fushun and Bagemaode ore-bearing areas are evaluated as the first-class favourable target areas for in situ conversion; eight ore-bearing areas such as Gaozhou, Maoming and Fuyu-Changchunling are the second-class favourable target areas, and 16 ore-bearing areas such as Tongchuan, Qidaoquanzi and Tanshanling are the future alternative areas for this purpose.

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