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Analysis of Kazakhstan Oil Shale Deposits in Accordance with Resource Estimation Practices for Consideration of Potential Shale Oil Reserves

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Abstract: Most oil shale deposits in Kazakhstan were estimated without detailed calculations of the grade and tonnages and included low confidence categories, i.e., Inferred, Off-Balance, and Non-Economic oil shales, on which cannot be given any oil reserves. An analysis of Kazakhstan oil shale deposits in accordance with resource estimation practices for consideration of potential shale oil tonnages has been produced. The developed methodology considers extraction and processing recoveries of conventional and unconventional mining methods. The methodology uses Monte Carlo modeling to estimate a range of oil content and oil recoveries and uses the event tree analysis to demonstrate how the initial oil shale material tonnages and grades go through various fault and success branches, considering probabilities distributions and estimating potential shale oil tones at the end. As a result, this estimation methodology has been validated by high-ranked resource category oil shale deposits, which demonstrated the range of potential shale oil in the range of 10.7–16.8 Mt at the 50% confidence level. The results will be used for further consideration in financial-economic feasibility studies, which must take into account operational and capital expenses, product sale prices and market, and social-environmental aspects.

Keywords: retorting; shale oil reserves; fault tree; probability distribution

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1. Introduction

The global quantity of oil shale resources has been estimated using various methods, though detailed methodologies for assessing commercial shale oil reserves are often lacking, where most attempts to estimate oil shale resources have relied on limited or unreliable data. Geological resources represent the total quantity of an oil shale material present on the Earth, regardless of whether it is economically or technically extractable. In contrast, shale oil reserves are the portions of the geological resources that are economically and technically viable to extract under current market conditions, technologies, and regulations. Thus, the economic potential of oil shale can be overestimated if it is based only on mineral resources and not considered extractable oil reserves. Factors like market prices, extraction costs, technical and technological advancements, environmental regulations, and infrastructure availability are critical in determining whether geological resources can transition into economically viable reserves [1–5].

About 25 of Kazakhstan's oil shale deposits were estimated using old Soviet Union standards [1] (State Commission on Mineral Resources, namely 'GKZ' in the Russian

language), and some of these estimations are based on potential oil shale material without proper calculations of the grade and tonnages including Inferred, Off-Balance, and Non-Economic oil shales. However, a few deposits have been estimated with A, B, and C 1 categories [1], which are approximately equal to Measured and Indicated categories in accordance with the International Committee for Mineral Reserve's International Reporting Standards (CRIRSCO) [2,3]. Moreover, some oil shale deposits were simultaneously mined during the development of coal seams and stored in the form of separate dumps until they were in demand in the raw materials market [1]. In addition to this, there is a shortage of existing methodologies that can be used to accurately estimate shale oil reserves. The laboratory-based Fisher assay method is not enough to present shale oil reserves because industrially proven retorting technologies to demonstrate oil recoveries are required [4–7]. The aim of this study is to analyze Kazakhstan oil shale deposits in accordance with resource estimation practices for consideration of potential shale oil reserves. In this study, deposits only with Indicated and Measured resources are considered for the estimation of potential shale oil reserves in Kazakhstan. The developed methodology considers variables in mineral resources, oil content, mining/extraction recoveries, and retorting recoveries to estimate potential shale oil tonnages. Shale oil properties for further refinery recoveries for final salable products are not within the scope of this study. The methodology uses the oil content estimated as a range of probabilities with the help of Monte Carlo modeling, as there are no comprehensive and detailed studies on tonnages for each grade. In the next stage, it estimates a range of probabilities for oil recoveries because of uncertainties in extraction methods and retorting technologies. The methodology uses a fault/event tree approach to demonstrate how the initial oil shale material tonnages and grades go through various fault and success branches to estimate potential shale oil tones at the end.

2. Kazakhstan Oil Shale Formations

Kazakhstan oil shale formations and deposits are presented in Figure 1.

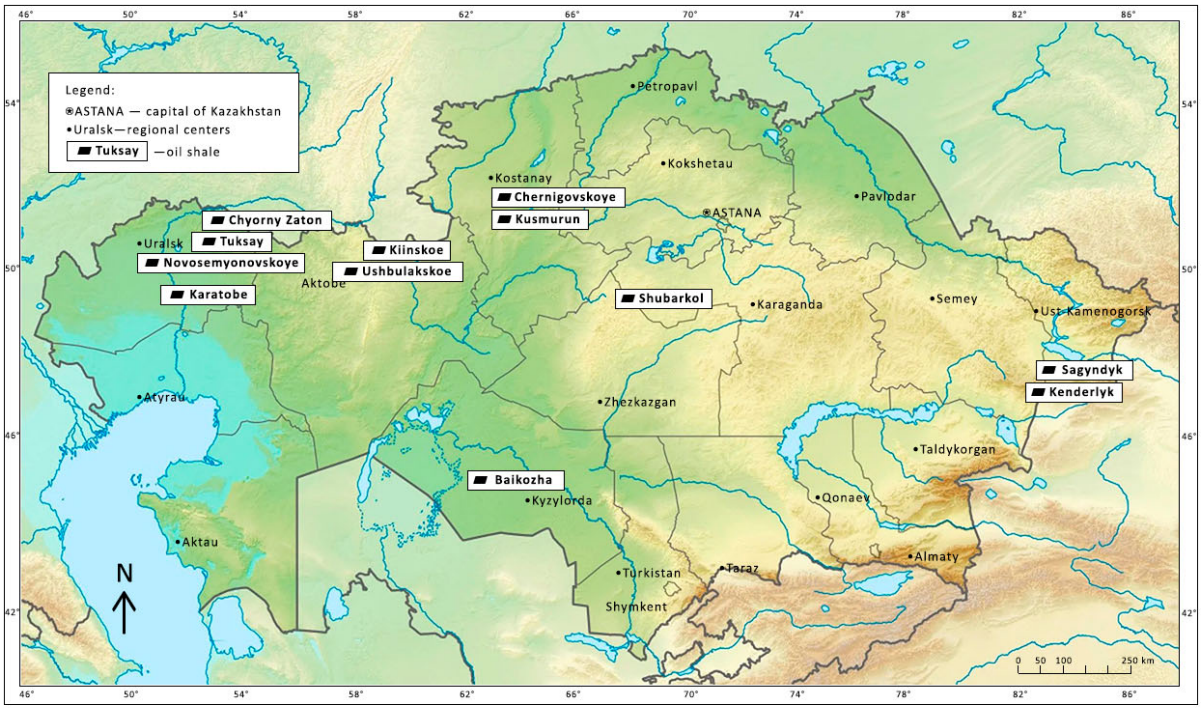


Figure 1. Kazakhstan oil shales map.

Oil shale formations in Kazakhstan are associated with the Upper Devonian, Lower Carboniferous, Permian, Medium, and Upper Jurassic and Paleogene periods. The Kender-

lyk in Eastern Kazakhstan, the Baikhozhinskoe oil shale deposits in Southern Kazakhstan, and the Ural group of deposits in Western Kazakhstan are connected to the Karatobe oil shale Formation and Turgayskiy lignite basin. The Kushmurun and the Chernigovskoye oil shale deposits are part of the Turgaiskiy Formation. The Algabas, the Cherniy Zaton, and the Tuksay oil shale deposits are all part of the Karatobe Formation. Additionally, some oil shales, i.e., the Shubarkol oil shale beds in the Karaganda region, occur alongside coal formations [8].

One of Kazakhstan's largest oil shale deposits is the Kenderlyk oil shale (Lower Permian Age), situated in the country's eastern region close to the Ust-Kamenogorsk city [9,10]. Kenderlyk contains about 708 million tons of oil shale material at an average depth of 260 m [9,10]. The Kalyn-Kara, the Luchshiy, the Karaungur, and the Saikan are the four seams that compose the Kenderlyk oil shale deposit. The Luchshiy seam is a comparatively basic structure that is 0.9–1.2 m thick. There are further interlayers of oil shales at 80 m above the Luchshiy with a shale oil content of 4.6–6.5% and a thickness of 0.1–0.4 m. The ash content is 71%, the hydrogen content is 8.2%, the nitrogen content is 0.1%, the oxygen content is 15%, the sulfur content is 1%, the carbon content is 75%, and the moisture content is 4% [8,10]. The Luchshiy seam has some individual samples with an oil content of 27%, while the average oil content is not higher than 10%. However, Golitsyn et al. [8] reported an oil content of 16–18%. The calorific value is 1430 kcal/kg [9–13]. The Kalyn-Kara seam is situated 0.3–0.5 m above the coal seam and has a thickness of 1.8–2.6 m. The ash content in this seam is 51.6%, the recovery of volatile compounds from a dry shale is 68–73%, and the organic content is 7.1–7.0% (for a combustible mass). Shale oil content is about 5–9%, which is quite low when compared to other oil shale seams [9]. The hydrogen content is 7.9%, carbon is 72%, nitrogen is 1.8%, oxygen is 17.3%, sulfur is 1%, and moisture is 3.4% [8–16]. The shale-bearing horizon appears 100–220 m above the base of the Karaungur seams. The seams are not always the same thickness; they range from 100 to 135 m along the Aiskaya anticline to 95 m along the River Maichat and 70 m close to the River Aba. The thickness of the seam drastically drops and loses its value north of the River Akkolka. Although the quality of the Karaungur seams varies along the strike as well as from seam to seam, the southern side of the deposit has better-quality oil shales. Three sets of oil shale in Layer I make up 0.70 m. A 0.16 m oil shale represents Layer II. An interlayered bituminous siltstone and oil shale with a total thickness of 1.21 m represents Layer III. Two oil shale sets with a total thickness of 8.64 m, separated by bituminous siltstone and sandstone interbedded with a total thickness of 2.18 m, represent Seam IV. Two oil shale sets with thicknesses of 0.61 and 0.16 m comprise Layer V. Layer VI has a thickness of 0.45 m and is located 5 m above Layer V. Oil shales have an oil content of 8.5% and calorific value of 1545 kcal/kg in the River Akkolka region. The quality of the oil shale rises as one moves south, and the average shale oil content of all seams is about 14.4% [9]. The ash content is 76.4%, moisture is 1%, hydrogen is 10.7%, sulfur is 1.4%, carbo is 75.6%, nitrogen is 2.3%, and oxygen is 15% [8–16]. Among the four seams of the Kenderlyk deposit, the Saikan is the least explored. Four productive horizons are found in the Saikan seam. Oil shales from three seams in the first horizon, which is 0.2–8.5 m thick. There are six seams in the upper portion of the second horizon, which is 70 m above the first, and they are 0.6–7 m thick, for a total thickness of 15.8 m. With thin interlayers of oil shales, bituminous rocks comprise the third and fourth horizons. Oil content ranges from 6% to 9% on average [9]. The ash content is 77.2%, moisture is 2.9%, hydrogen is 9.8%, sulfur is 0.5%, carbon is 70.6%, nitrogen is 3.5%, and oxygen is 15.6% [8–16]. A generalized stratigraphic column and cross-sections for the Kendyrlyk deposit are presented in Appendix A, Figure A1.

Another group of oil shale deposits in Western and Northern Kazakhstan is the Permian Group. Coal and oil shales, mudstones, siltstones, and sandstones alternately

compose the Kushmurun deposit of the Turgaiskiy Formation, which is about 300 m deep. The oil shales are estimated at 123 Mt [1], including A, B, and C1 categories. According to Golitsyn et al. [8], ash content is 55%, volatile substance is 63%, moisture is 7%, hydrogen is 7.2%, sulfur is 2.6%, carbon is 66%, and the calorific value of the oil shale is 1852 kcal/kg.

The Chernigovskoye deposit is limited to a long, narrow-down warping that extends northeast. The down warping is 20 km long, 1–2 km wide, and approximately 100 m deep. The strata of oil shale are roughly 23 m thick overall. There are over 135 million tons (A + B + C1 categories) of oil shale material in the Chernogovskoye deposit [1]. The ash content is 56%, moisture is 6%, and the content of the hydrogen, sulfur, and carbon is 6.7%, 0.4%, and 63.6%, respectively [8],

The Karatobe deposit is situated in the West Kazakhstan district, 225 km southeast of the town of Uralsk. The brown shales of the Algabas deposit in the Karatobe Formation are typically slabby, calcareous, and have a high calorific value of 1900–3250 kcal/kg. The ash content is 33–73%, volatile matter compounds are 42–75%, moisture is 7.2%, and shale oil is up to 23%. According to the authors of [17], 5.6 million tons of oil shale material are estimated here.

The Tuksay deposit (Neogene-Quaternary Formation) is situated 20 km south of the Cherny Zaton deposit and 10 km north of the Algabas station. There are six seams in the shale-bearing strata of the Tuksay deposit. The primary oil shale seam is 25 m deep and 1.05 to 2.0 m thick. The average calorific value is 2625 kcal/kg, and the average ash content is 50.19%. There are roughly 5 million tons of oil shale material [17]. The Tuksay brown oil shale has a shale oil content of 14.2%, with 14.9% pyrolytic water, 54.9% semicoke, and 16% gases and losses. The chemical composition includes the following: $Si0_2$—50.6%, Fe_20_3—5.7%, Al_20_3—20.4%, CaO—11.8%, MgO—29%, Si—1.3%, Ni—0.008, $V20_5$—0.01%, Mn—0.014%, Pb-0.004%, and Cu—0.001% [17].

The Novosemyonovskoe deposit (Upper Jurassic) is 70 km east of Uralsk, 7–8 km south of the Algabas station, and close to the Novosemionovka village. Seams of oil shales are found in the grey and dark grey bituminous clays that compose the lower, shale-bearing portion of the Nizhnevolzhsky suite, which is about 30 m thick. The deposit contains 12 oil shale seams total, which are situated 60 m deep. A 13 m thick layer of clays divides the two horizons formed by the combination of all seams. There are two workable seams of oil shales and six unworkable seams on the lower horizon, which are primarily made up of grey clays and infrequently marly clays. Three interlayers of unworkable shales and one workable seam of oil shales are found in the upper horizon, which is composed of marly and saprolite clays. The overall seam thickness ranges from 8.2 to 13.3 m. Consistently thick seams are workable. While the Seam III (0.9–1.15 m) has a simple structure and is made up completely of brown oil shales, the Seam IX (thickness is 2–2.7 m) and the Seam VII (0.9–1.1 m) have a complex structure. They have a high ash content and shale oil content of up to 8%. Oil shales have a high sulfur content (0.4–17%). The Seam III is the best of the three viable seams at the deposit. The estimated oil shale material in the three seams was 5.9 Mt, from which A+ B categories have 3.9 Mt [9].

The Cherniy Zaton (Neogene-Quaternary) oil shale deposit is located 30 m below the ground's surface and has a seam thickness of 2.0 to 2.9 m. There are two types of oil shales, which vary in quality: dark grey and brown. The dark grey has an average ash content of no more than 70%. In contrast, the brown oil shale typically contains 22–61% ash, the ash content of brown shales is 25–70%, and moisture is 7–25%. The caloric value is 1400–4224 kcal/kg, with an average of 2100 kcal/kg [9]. Oil shale material reached 4 Mt with an oil content of 24.6%; moisture is 7.5%, sulfur grades range from 1.0 to 8.9%, and semicoke is 62.19%.

There is an additional recognized oil shale formation in East Kazakhstan situated in the Tarbagatai region, 4 km east of the Tologaiskoe coal deposit, named Karaadyr, which is, likewise, Lower Permian in age. Constrained to the central section of the Karaungur suite, the productive horizon has a thickness of roughly 45 m and is made up of up to 16 oil shale seams and interlayers at a total thickness of 8.4 m; the thickness of each seam varies from 0.3 to 4.6 m. The oil content is 10.1%, and the calorific value is 2000 kcal/kg. There is approximately 2.3 Mt of oil shale at a depth of 100 m [9].

The Sagyndyk deposit is situated 48 km south of the Topolev Mys village on Lake Zaisan in the Tarbagatai region, on the western side of the Manrak Mountain. Sagyndyk deposit is related to Lower Permian shale-bearing rocks with a thickness of roughly 140 m. There are two intricate shale seams on the lower horizon, separated by a bed of sandy-clayey rocks that is 9 m deep. The second (upper) seam is 2.35 m thick and contains 1.55 m of oil shale, whereas the first seam is 3 m thick overall and contains 0.33 m of oil shale. In the top horizon, two beds of oil shales with thicknesses of 0.16 and 0.32 m have been identified. Shales contain 74–85% ash, are thin, dark brown, and low in sulfur, containing 40,000 tons of oil shales [9,10].

Deposits of the Aktubinsk group are limited to the Kiin suite of the Famenian stage of the Upper Devonian and are only found on the western slope of the Mugodzhary hills, which lie east and northeast of the city of Aktobe. Kiinskoe and Ushbulakskoe are the two deposits that are known to exist here. The Kiinskoe deposit is situated in the upper Kii River stream in the Stepny area of Aktubinsk oblast. Only the upper reaches of the River Kii are exposed to the Kiin shale-bearing suite. Oil shales with interlayers ranging in thickness from 0.1 to 20 m have been discovered in this portion of the Kiin complex. Five seams are 36.8 m thick. The seams thickness are 2.6 m thick for Seam I, 5.9 m thick for Seam II, 1.7 m thick for Seam III, 8.83 m thick for Seam IV, and 20 m thick for Seam V. The oil shale calorific value is 1537 kcal/kg for a dry substance; the sulfur content is 0.2% –1.04%, and the ash content of oil shales ranges from 70 to 92%. The oil content is 4.1–6.5%, 86–93% is semicoke, and 2.0–3.7% is pyrolitic water. Shale oil has a specific weight of 0.82 and is a pale reddish-brown liquid that comprises the following: C—85%, H—10.4%, N—2.76%, and O—1.76%. The shale oil calorific value is 10,100 kcal/kg. Because of their high ash content, limited shale oil content, and sulfur concentration, the oil shales at the deposit have low value at the moment. The estimated total oil shale material is 10 Mt [9].

The Ushbulakskoe deposit (Eocene Age) is situated 17–18 km northwest of the Novorossiskoe village and 42–45 km northeast of the town of Aktobe. The argillaceous, siliceous-argillaceous, marly sandstones, conglomerates, and limestone compose the deposit, which includes a seam of oil shales. Dark brown to black oil shales constitute the 1–2 m thick seam, whereas the compact, robust kind compose the lower 0.9 m part. The moisture ranges from 4.45 to 7.57%, the ash ranges from 67 to 75%, the sulfur ranges from 1 to 4%, and the shale oil content ranges from 7.6 to 14.2% [9,10].

The Baikhozha deposit (Eocene Age) is situated 2.5–4.5 km southeast of the Baikhozha railway station in the Kazalinsky district of the Kyzyl–Orda oblast, on the left and right banks of the River Syrdari. The shales have an ash content of 55–70% and 1.7–1.7% sulfur; the oil content is 3–4%. Oil shale material is about 8.8 Mt [9].

The oil shales of the Shubarkol deposit range in thickness from 1.1 to 7.7 m. The Soviet Union Governmental Committee of Reserves assessed that 409 million tons of oil shale material (Off-Balance, C2 category) with an average net calorific value of 7.2 MJ/kg (1720 kcal/kg) were present in the Shubarkol deposit ('GKZ USSR, 1987, protocol # 2211-K') at a minimum seam thickness of 1.0 m [17]. The average density of oil shale is 1.9 t/m^3, moisture is 3.1%, and its compressive strength is 12.5 MPa [18,19]. Shubarkol oil shale has yielded 73.5% semicoke, 9.8% pyrolytic water, and 5.7% oil. The mineral portion's

chemical composition includes the following: Si_2—56.5%, Fe_20_3—11%, Al_20_3—27.3%, and trace amounts of CaO [19]. A generalized map and cross-sections for the Shubarkol deposit are presented in Appendix A, Figure A2.

Summary Table 1 below presents tonnages, oil content, calorific value, depth, thickness, moisture, sulfur, carbon, ash, and volatile of Kazakhstan oil shale deposits.

Table 1. Kazakhstan's oil shale deposits characteristics [1,8–19].

Deposit Name	Oil Shales, Mt	Oil, %	Calorific Value, kcal/kg	Depth, m	Thickness, m	Moisture, %	Sulfur, %	Carbon, %	Ash, %	Volatiles, %
Kalynkara (Kenderlyk)	533 + 155 + 20 *	5–9	–	260	2.2	3.4	1.0	72.0	35.8	70.5
Luchshiy (Kenderlyk)		16–18	1430		1.1	4.0	1.0	75.0	71.0	–
Karaungur (Kenderlyk)		10–15	1545		4.4	1.0	1.4	75.6	76.4	–
Saikan (Kenderlyk)		6–9	–		4.1	2.9	0.5	70.6	77.2	–
Sagyndyk	0.04	–	–	140	0.9	–	0.7	–	79.3	12.8
Karaadyr	2.3	10.1	2000	100	2.5	–	–	–	–	–
Chyorny Zaton	4.0	24.6	1900–4224	30	2.5	7.3	5.0	66.2	47.2	62.2
Tuksay	5.0 *	13.0–14.2	2625	25	1.0	–	–	–	44.9	63.5
Novosemyonovskoe	5.9 (3.9) *	8	2575	40	1.5	–	8.7	–	53.0	58.5
Karatobe	5.6	23	1900–3250	35	0.4	7.2	3.8	–	47.6	39.3
Kushmurun	123 *	–	1852	300	–	7.0	2.6	66.0	55.0	63.0
Chernigovskoye	135 *	–	–	100	23.0	6.0	0.4	63.6	58.0	66.0
Kiinskoe	10	4.1–6.5	1537	–	10.1	–	1.3	72.0	81.0	19.3
Ushbulakskoe	–	7.6–14.2	-	–	1.5	6.0	2.5	–	71.0	57.9
Baikozha	8.8 *	3–4	-	15	0.1	–	3.9	–	63.3	13.5

Deposits marked with a star (*) have been estimated with A, B, and C 1 categories, which are approximately equal to Measured and Indicated categories. Kushmurun and Chernigoskoye have not reported any oil content or calorific value. At the Kushmurun, Chernigovskoye and Shubarkol oil shales are under development because of mining coal below seams. Novosemyonovskoe, Tuksay, and Baikozha have low tonnages compared to Shubarkol and Kenderlyk. Thus, deposits with Indicated and Measures resources are considered to validate a methodology for the estimation of potential shale oil tonnages in Kazakhstan.

3. Methodology

The proposed estimation methodology algorithm in Figure 2 starts from general oil shale formation tonnages for a prospective material (Step 1), which typically are Non-Economic or unrecoverable. At the next step (Step 2), by continuing geological exploration in case of success, oil shales can be estimated as Inferred material that can be named as a contingent resource. After that, the algorithm suggests estimating Indicated and Measured Geological Resources by increasing the confidence level that must report tonnages and grades (Step 3). Then, Measured and Indicated Mineral Resources will be estimated to Probable and Proved Reserves through detailed study of economic, technical, and operational aspects of mining, processing, market prices, infrastructure, and environmental considerations named as the 'modifying factors' (step 4). In the final Step 5, received shale oil might require additional refinery processing necessary for final commercial products (Figure 2).

A fault/event tree approach is then applied to illustrate how the initial oil shale material tonnages and grades go through various fault and success branches, ultimately estimating potential shale oil tonnages (Figure 3). The event tree is initiated from Step 1 (oil shale formations) of the methodology algorithm shown in Figure 1 and continues splitting by branches using data from Steps 2–4, representing tonnages and grades for different resource categories and estimating their success or failure. Indicated and Measured Resources are used as Success (True), and Inferred and Off Balance are failed (False) because of their low confidence level to be presented for any economic estimations. The success branch is continuing to grow to show passes for the various reporting technologies considering mining and processing recoveries. Then, each restoring method is split into branches for the estimation of minimum, most likely, and maximum shale oil recoveries to demonstrate all probable outcomes. A forced branch highlighted in red is to focus on the most likely outcomes. Brunches with 'High' are assumed to be False for not overestimating the outcomes (Figure 3).

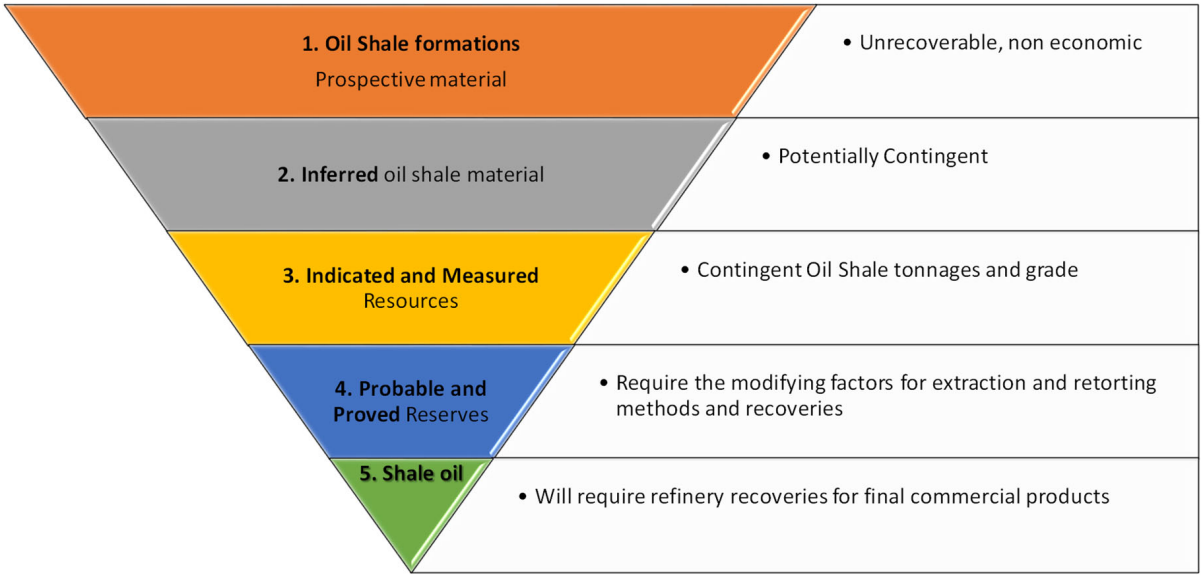


Figure 2. Shale oil estimation algorithm.

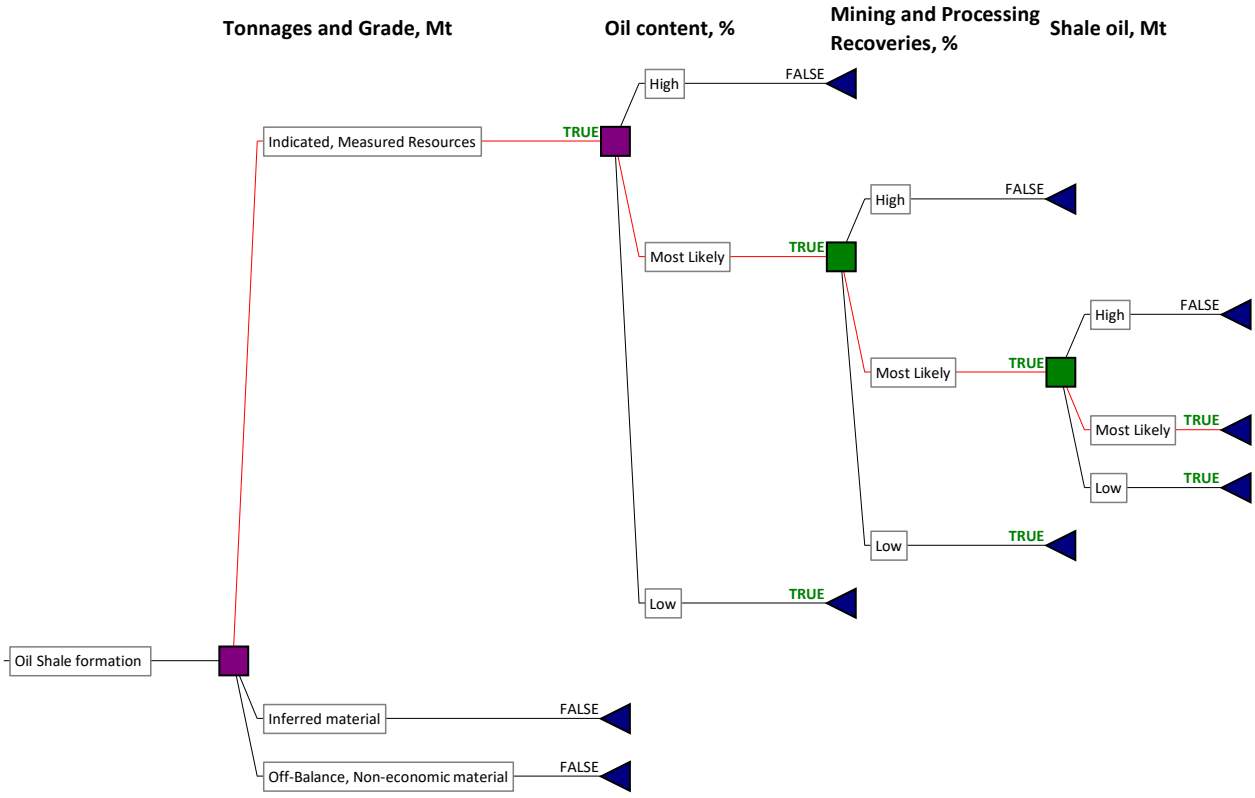


Figure 3. Event/fault tree analysis.

Monte Carlo simulation is used for building models demonstrating possible outcomes. The distribution of probability, which is a range of values, replaces any uncertainty factor when producing the models. After that, numerous computations of the outcomes are produced, at every turn establishing a variety of stochastic variables for the probability functions. Monte Carlo modeling helps to determine the value distribution of the probable numbers with several likely outcome values [20–22]. The proposed methodology employs Monte Carlo modeling to estimate oil content as a range of probabilities, addressing the lack of comprehensive and detailed studies on tonnages for each grade. In addition, it determines a range of probabilities for shale oil recoveries, accounting for uncertainties

in extraction methods and retorting technologies. The modeling utilizes analyzed values from Tables 1 and 2 (below). Potential shale oil tonnages are expressed in terms of their key parameters, estimating variables in mineral resources, oil content, mining/extraction recoveries, and retorting recoveries. Standard statistical distributions can be chosen to represent the variability of each parameter. Monte Carlo modeling of shale oil potential tonnages (SOmc) will be estimated by the following formula:

$$SOmc = GR * OC * MR * RR \quad (1)$$

where GR is the geological resource, OC is the oil content, MR is mining and extraction recoveries, and RR is retorting recoveries. For this study, Palisade@Risk 8.5 software was used for Monte Carlo modeling.

Some oil shale retorting technologies are compared in Table 2 to demonstrate oil recoveries under particular oil content using conventional (regular retorting method, i.e., Galoter type) and unconventional (i.e., Shell ICP—in situ retorting, Red Leaf EcoShale—ex situ retorting) technologies. Conventional ground retort with a solid heat carrier named the Galoter type uses a pyrolysis process for the processing of fractional oil shale [23,24]. In situ retorting technology is used to extract liquid and gaseous hydrocarbons by drilling wells into deposits and adding more heat to the formation using electrical heating, high-temperature liquid injection (steam, gas), or air [25,26]. Ex situ retorting involves open-pit extraction of oil shale, followed by thermochemical processing to produce liquid fuels [27].

Table 2. Oil shale retorting technologies.

Oil Shale Retorting Technologies	Oil Content (%)	Oil Recovery (%)
Shell ICP, Green River [26–28]	11	60–90
Sanjiang-type rectangular pilot-scale retort [29]	15	85–86
Red Leaf, EcoShale in capsule retorting [30]	11	65–82
Galoter solid-heat carrier technology [31–33]	23	75–92
Kiviter gaseous-heat carrier technology [34]	22	75–80
In situ superheated steam injection (MTI) [35,36]	4	~71
Fushun oil shale [37–42]	7	~86

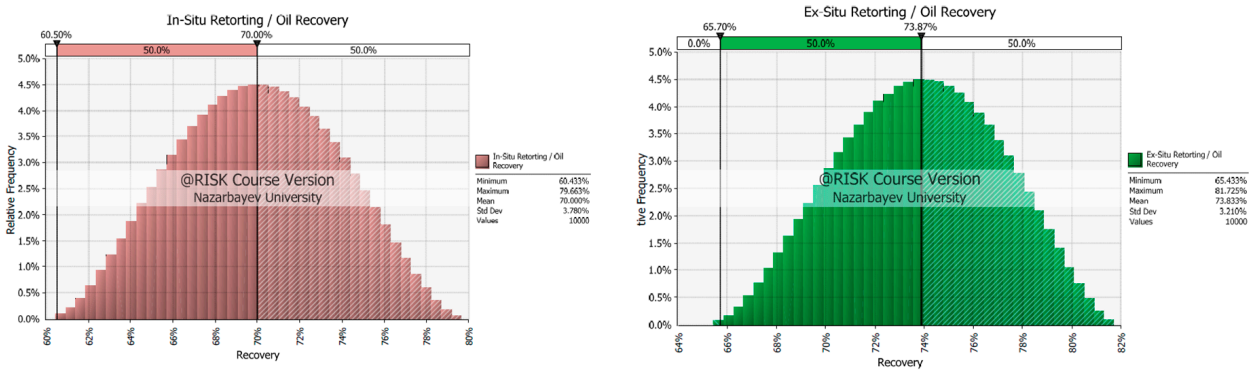
However, these unconventional technologies are still not proven by any industrial value installations, and shale oil recovery factors for them are not yet certain, so they can be presented at a low confidence level. Thus, shale oil potential tonnages can be presented only through probability distributions because of uncertainties in extraction methods, retorting technologies, and modifying factors.

4. Results

4.1. Retorting Recoveries

Considering the retorting recoveries specified in Table 2, Monte Carlo simulation produces possible outcomes for the in situ and the ex situ retorting technologies. Industrially proved conventional retorting Galoter type has a range of oil recoveries of 76–92% at a 90% confidence level [7]. The in situ retorting recoveries are estimated in the range of 61–70%, and the ex situ recoveries have a range of 66–74%, only at 50% or lower confidence level (Figure 4). The lack of industrially proven projects generates low confidence levels on recoveries for unconventional methods.

These processed data will be used for the fault tree analysis to estimate potential shale oil tonnages.



(**a**) (**b**)

Figure 4. Oil retorting recoveries (**a**) the in situ and (**b**) the ex situ.

4.2. Kendyrlyk Oil Shales

The Kendyrlyk oil shale deposit contains 708 Mt of some oil shale material. from which 155 Mt are oil shales of the Inferred category and 20 Mt are estimated as Measured and Indicated according to the 'GKZ' category (A + B + C1). Oil content was considered for many different seams and has not been presented at an average value for the specified tonnages. Thus, it has been run through the Monte Carlo simulation and showed a range of oil content from 4.4 to 9.3%, which is well fitted with the Beta General distribution (Figure 5).

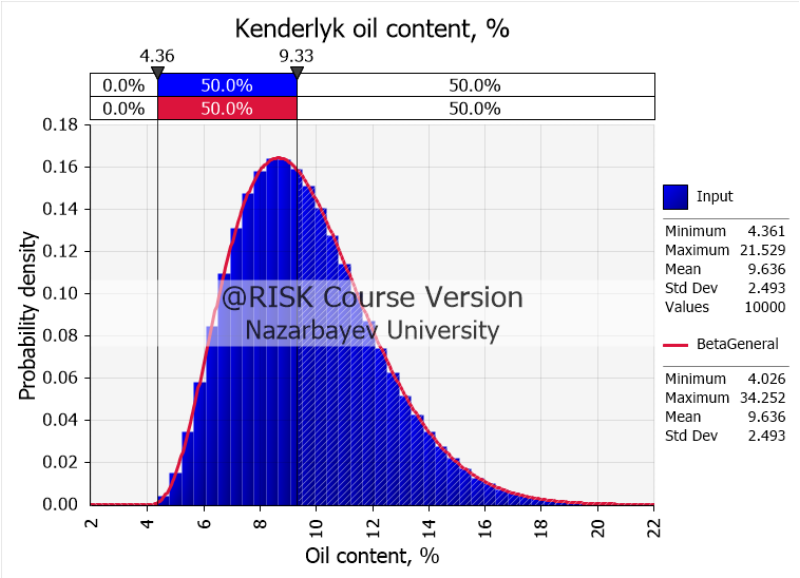


Figure 5. Kenderlyk oil content distributions.

Event tree analysis presented in Figure 6 shows potential shale oil tonnages that can be produced using conventional retorting and unconventional in situ retorting technologies. The event tree considered (TRUE) only for the high resources category (Indicated and Measured) for estimation of oil recoveries and mining (extraction) losses. Inferred materials of 155 Mt and 533 Mt have no value and, therefore, are added to the event tree as FALSE-ended branches. Mining losses are assumed to be 5–10%, which is typically accepted for conceptual-level estimations and proved by industrial expertise. Extraction losses for in situ retorting are assumed to be 10–15% [26–28]. Retorting recoveries are summarized in Table 2 and analyzed using Monte Carlo modeling in Figure 4, which was used for the event tree analysis shown in Figure 6.

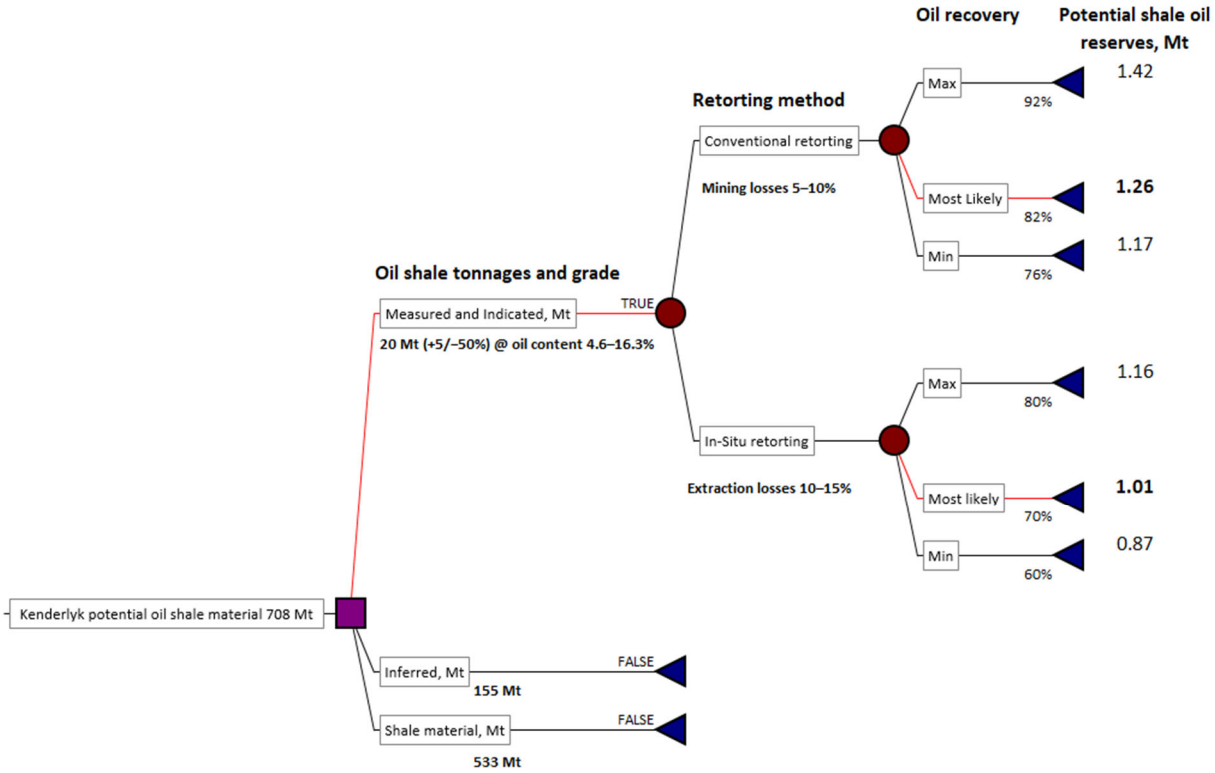
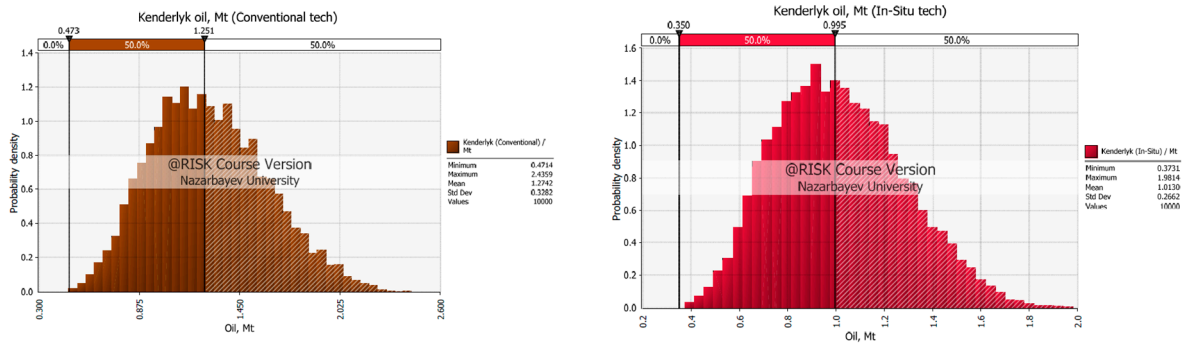


Figure 6. Kenderlyk event tree analysis.

As a result, for the conventional retorting, the Most Likely branch shows that potential oil can be produced at a value of 1.26 Mt and for the in situ retorting at 1.01 Mt, accordingly (Figure 4). Figure 7 demonstrates the Kenderlyk potential shale oil tonnages from the conventional technology, which can be in a range of 0.5–1.3 Mt, and from the in situ technology, in a range of 0.4–1.0 Mt at a 50% confidence level.



(**a**) Oil from Conventional technology (**b**) Oil from in situ technology

Figure 7. Kenderlyk potential shale oil tonnages (**a**) Oil from the conventional technology; (**b**) Oil from the in situ technology.

4.3. Shubarkol Oil Shales

The oil shale is situated above the productive coal seam, which is currently mined by the local mining company and stockpiled separately as a low-grade material. Due to the oil shale's potential to self-ignite in 3 to 5 months if left exposed, the oil shale is backfilled in the lower levels of the mined-out pit and covered with clay. The Shubarkol oil shale deposit contains 409 Mt of Inferred material (C2) with an oil content of 5.3%. Approximately 61% of the total oil shale amount is already mined, and, therefore, it is proposed to use the ex situ retorting technology for this mined part; for the rest of the oil shales, it can be chosen

as both the conventional and the unconventional retorting technologies. Monte Carlo simulation results showed a range of oil content from 4.9 to 5.2% at an 85% confidence level as this mined material underwent lab test works (Figure 8).

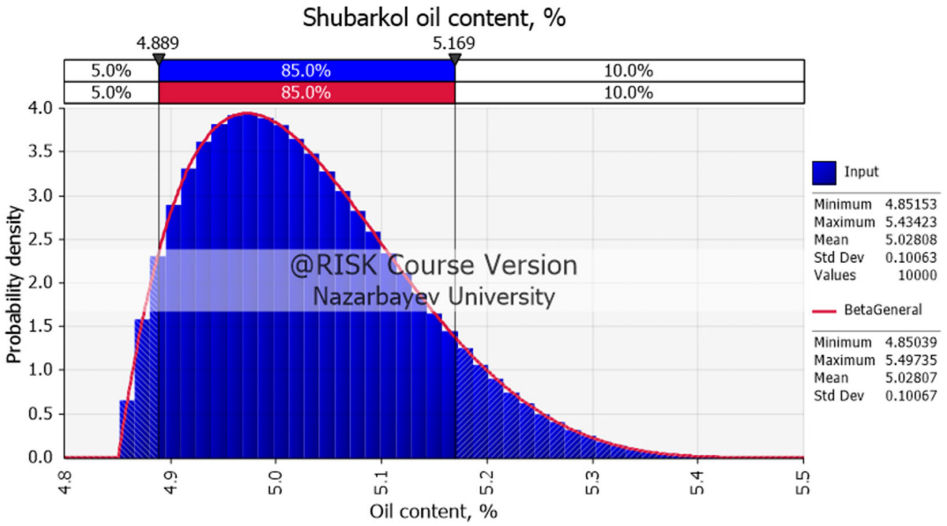


Figure 8. Shubarkol oil content distribution.

Event tree analysis in Figure 9 shows potential shale oil tonnages that can be produced using conventional retorting and unconventional ex situ retorting technologies. The event tree has two main branches: the mined and the unmined oil shale. Mining losses are assumed to be 5–10% for the unmined oil shale and 8–10% for the mined oil shale.

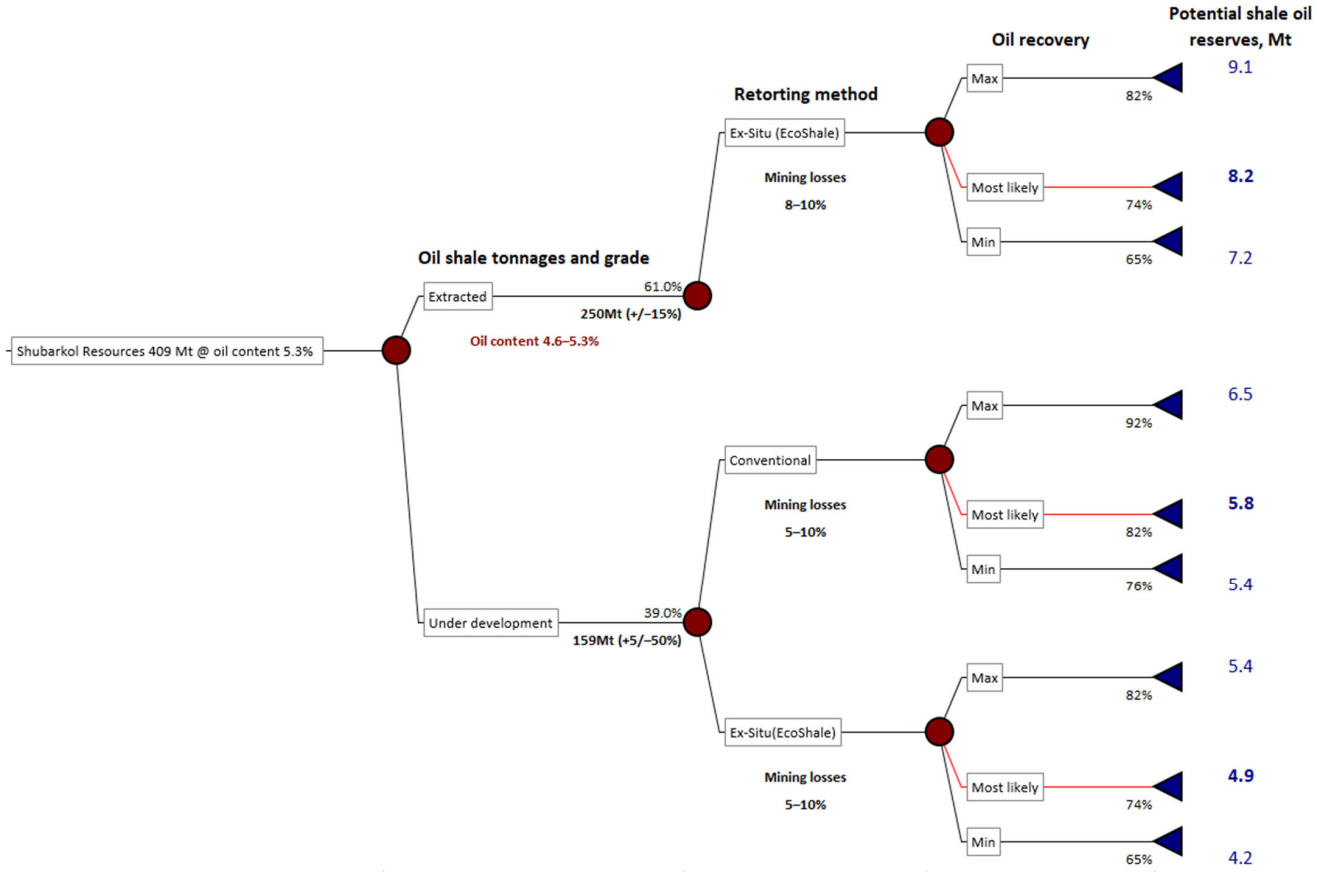


Figure 9. Shubarkol event tree analysis.

For the mined oil shale using the unconventional retorting, the Most Likely branch shows that projective shale oil can be produced in a value of 8.2 Mt, the unmined material with the unconventional technology can receive 4.9 Mt, and with the conventional 5.8 Mt (Figure 9).

Figure 10 demonstrates that from the mined oil shale using conventional technology, projective shale oil can be in a range of 4.7–7.7 Mt at a 50% confidence level. Figure 11 shows that from unmined material, conventional technology can produce a range of 3.4–5.9 Mt and the unconventional 2.8–5.0 Mt, accordingly, at a 50% confidence level.

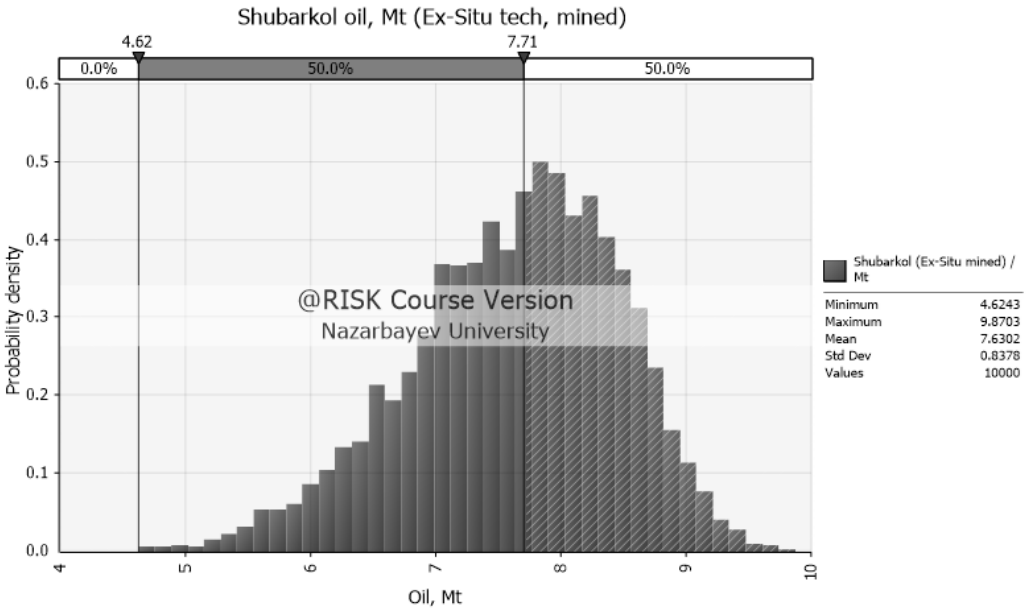
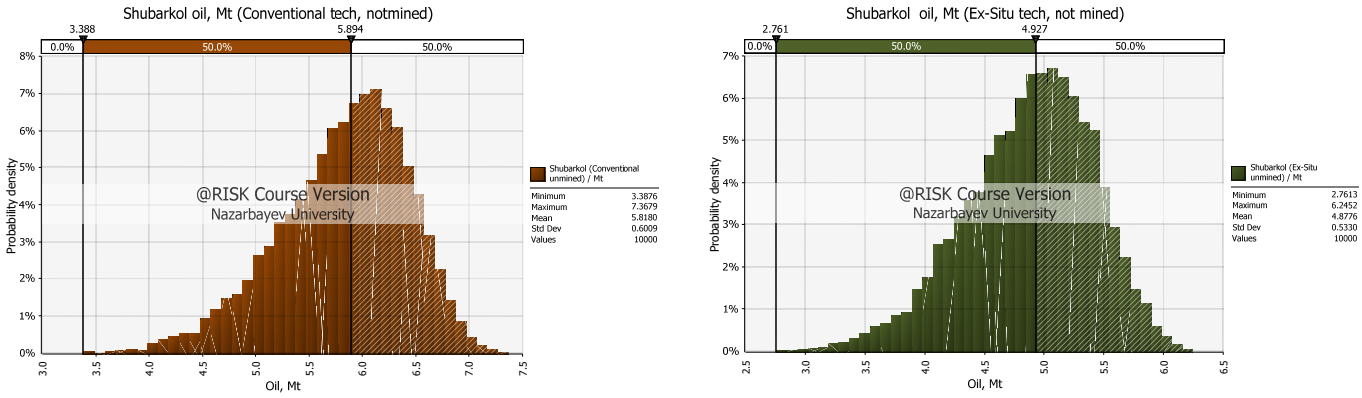


Figure 10. Shubarkol potential shale oil tonnages from the mined (stockpiled) material.



(**a**) Oil from Conventional technology (**b**) Oil from ex situ technology

Figure 11. Shubarkol potential shale oil tonnages from unmined resources (**a**) Oil from the conventional technology; (**b**) Oil from the ex situ technology.

5. Discussions

Oil shale resources and reserves are evaluated using a variety of methodologies that combine geological, chemical, and technical considerations to determine the potential for hydrocarbon extraction [2–4,43–50]. The estimation approaches listed above can be broadly classified as qualitative or quantitative evaluations, with each applying different criteria and models to estimate oil shale resources and reserves [33,43–52]. According to Wang et al. [44], both the statistical method and the analogy method can theoretically be used to estimate oil shale resources. However, the statistical method requires a certain amount

of production data, while the analogy method requires scaling a site with a higher degree of exploration that is similar to the geological conditions. The authors suggest using the oil content as a key parameter for evaluating shale oil resources. Also, studying several estimation methods, the authors determined that the parameters used in the volumetric method for evaluating oil shale reserves usually include oil shale volume, density, oil content, correction factor for light hydrocarbons and heavy hydrocarbons, oil saturation, and porosity [45–50]. However, most approaches for the assessment of oil shale resources and reserves vary considerably, resulting in inconsistent results. For example, some research uses mathematical techniques to estimate reserves [53,54], whereas other authors [1,4,8–10] rely on empirical relationships without a coherent framework. Dyni [4] stated that the Kenderlyk deposit has 400 Mt of shale oil in place, which seems to be an overestimated assumption. These stated oil tonnages are thousands of times erroneously higher than their real value. Azizov and Vlasov also argued that Kenderlyk has 4075 Mt of oil shale material with a grade of 4.6–10%, where only 708 Mt has economic potential. These statements might confuse readers when it comes to a simple estimation based on low confidence numbers and receiving overestimated shale oil tonnages: i.e., 708 Mt at 10% of oil content is about 71 Mt of shale oil. However, 708 Mt is just Inferred material on which there cannot be given any assumption on mineral resources and not even on mineable/extractable reserves. The developed methodology demonstrates the necessary steps and approaches to estimate projective shale oil tonnages. This study methodology utilizes stochastic modeling because deterministic models for shale oil reserves estimates cannot account for the variability of oil content and mining and processing recoveries and thus cannot be used for consideration of these unpredictable factors. In a very simple estimation, using a deterministic model, shale oil tonnages could be estimated by way of multiplication of estimated geological resource tonnages on oil content and recovery factors. In this case, for example, 20 Mt of Kenderlyk oil shale will give about 1.7 Mt of shale oil, which is not correct in terms of reserves estimation approaches and will lead to high discrepancies when it comes to the operational stage. This study demonstrated that Kenderlyk could receive a range of 0.5–1.3 Mt at 50% confidence level projected shale oil tonnages. To improve this confidence level of 50%, a detailed feasibility study must be performed considering proven industrial technologies and modifying factors. The recovery factor, which considers the percentage of oil that can be technically and economically recovered from the oil shale, is a major source of uncertainty. Recovery factors can vary significantly depending on the extraction method (mining vs. in situ retorting). Speirs et al. [2] highlight the wide range of reported recovery factors and the challenges in estimating them for unproven technologies. However, retorting technologies were not discussed in the shale oil reserves estimation approaches and methods in terms of recoveries for conventional and unconventional mining. The unconventional retorting methods and technologies have been compared in this study, and it is estimated that retorting recovery distribution can be in a range of 60–74% at a 50% or lower confidence level. The lack of industrially proved oil shale retorting projects has a very low confidence level for recoveries using unconventional methods. According to this, the study produced projective shale oil estimation for the Kenderlyk, Shubarkol, Novosemyonovskoe, Tuksay, and Baikozha deposits, which have Indicated and Measured geological resources. Thus, Novosemyonovskoe has a range of 0.22–0.24 Mt, Tuksay has 0.47–0.51 Mt, and Baikozha has 0.19–0.25 Mt at a 50% or lower confidence level.

As a result, the methodology has been validated by these five oil shale deposits and demonstrated projected shale oil in a range of 10.7–15.8 Mt at a confidence level of 50% (Figure 12). The reliability of these findings can be evaluated by evidence of real data that supports the obtained values that were received from the operational open cast 'Shubarkol', which produces regular lab test works and surveys on material movement. In addition,

the developed methodology was validated on data from Estonian oil shale industrial operations, whose experience received over 50 years demonstrated reliable results [7]. For the particular oil shale deposits in Kazakhstan, evidence that supports the obtained values can be presented through additional exploration drilling and a detailed feasibility study because oil shales in Kazakhstan are not well explored, and there are no industrial applications. The methodology can propose necessary steps and provide a probable range of outcomes so that stakeholders can understand the values and not get confused with some other overestimated numbers. However, retorting recoveries must be proved for each specific oil shale type. This methodology does not consider any financial-economical estimations, which will require feasibility studies taking into account operational and capital expenses, product sale prices and market, and social- environmental aspects.

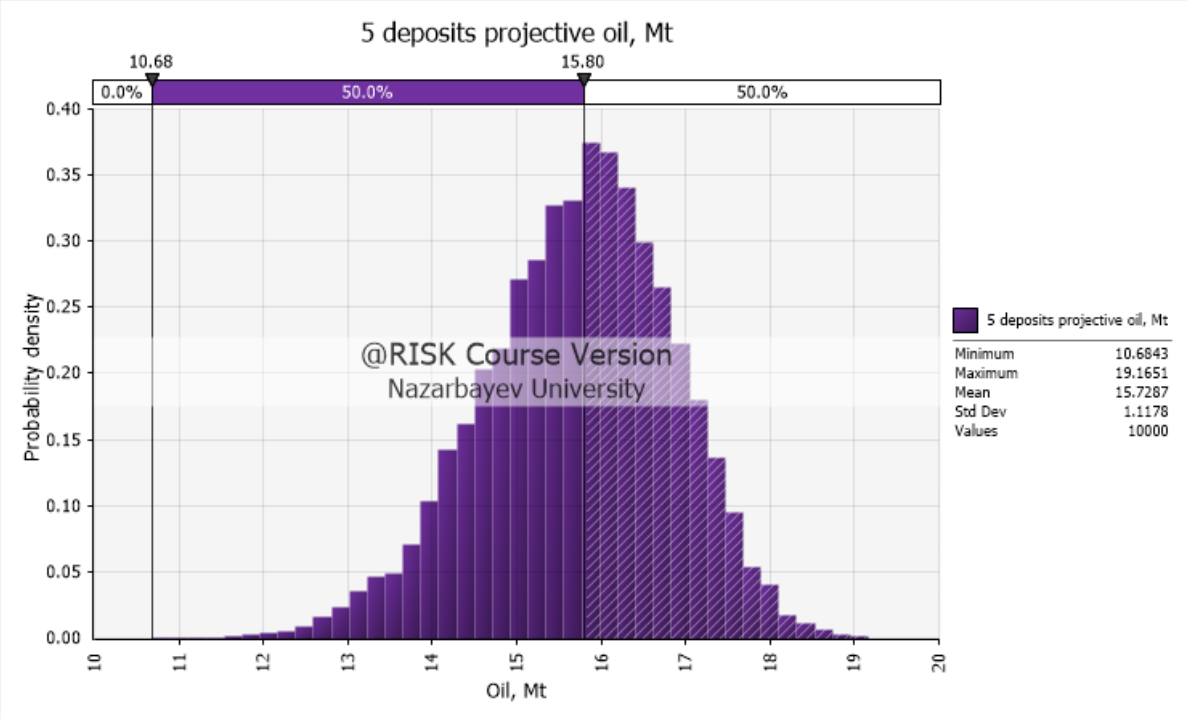


Figure 12. Five deposits of potential shale oil reserves.

6. Conclusions

Analysis of Kazakhstan oil shale deposits in accordance with resource estimation practices for consideration of potential shale oil reserves has been produced. The developed methodology considers variables in mineral resources, oil content, mining/extraction recoveries, and retorting recoveries to estimate potential shale oil tonnages. The methodology utilize Monte Carlo modeling to estimate a range of the outcomes, and the event tree analysis demonstrated how the initial oil shale material tonnages and grades go through various fault and success branches, considering probabilities distributions and estimating potential shale oil tones at the end. As a result, the methodology utilizes the following retorting recoveries:

- The industrially proved conventional retorting the Galoter retort type, which has a range of oil recoveries of 76–92% at a 90% confidence level;
- The in situ retorting recoveries are in the range of 61–70% at a 50% or lower confidence level;
- The ex situ recoveries are in the range of 66–74% at 50% or lower confidence level

Lack of industrially proven projects has low confidence in recoveries on the unconventional methods; however, these may be beneficial for future innovative and sustainable projects. As a result, the estimation methodology has been validated by data from five oil shale deposits, which demonstrated the range of potential shale oil of 10.7–16.8 Mt at a 50% confidence level. The results will be used for further consideration in financial-economic feasibility studies, which must take into account operational and capital expenses, product sale prices and market, and social-environmental aspects.

Author Contributions: Conceptualisation, S.S.; methodology, S.S.; software, S.S.; validation, S.S.; formal analysis, S.S.; investigation, S.S.; resources, S.S.; data curation, S.S.; writing—original draft preparation, S.S., R.K. and A.K.; writing—review and editing, S.S. and A.K.; visualization, S.S.; supervision, S.S.; project administration, S.S.; funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data are available on request due to privacy restrictions. The data presented in this study are available on request from the corresponding author. The data are not publicly available due to confidentiality agreements between parties.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

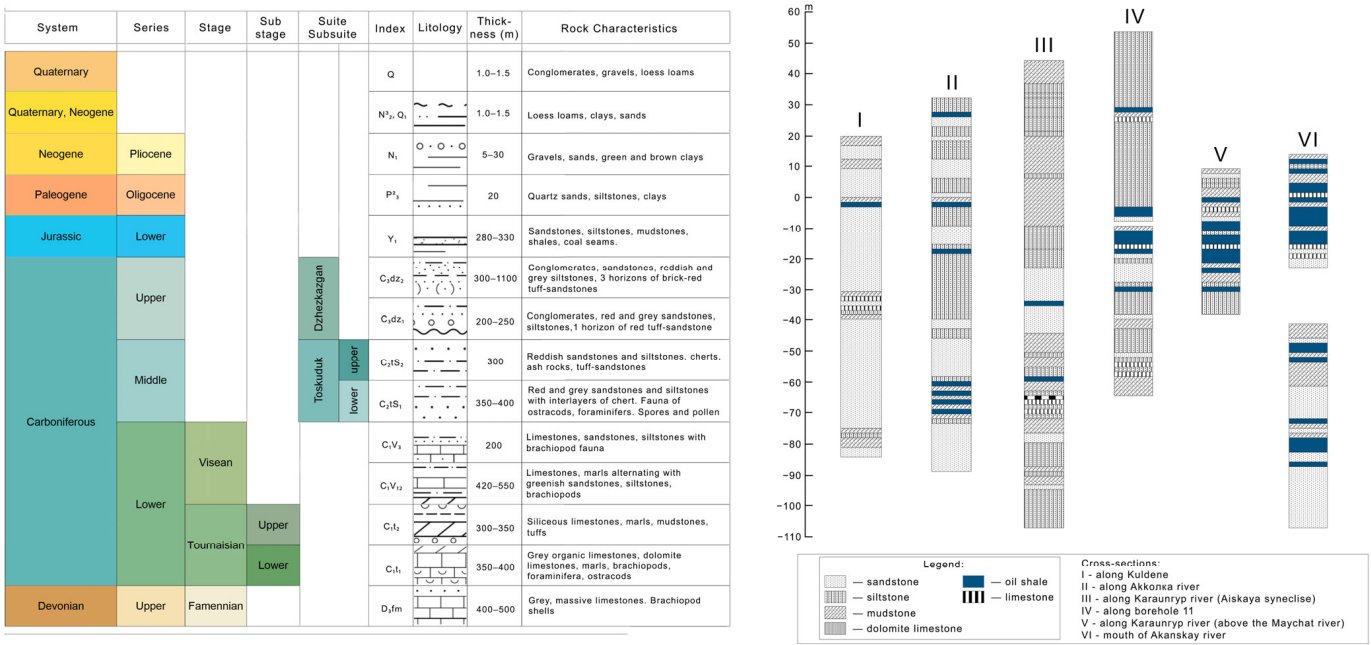

Figure A1. A generalized stratigraphic column and cross-sections for Kendyrlyk deposit [10].

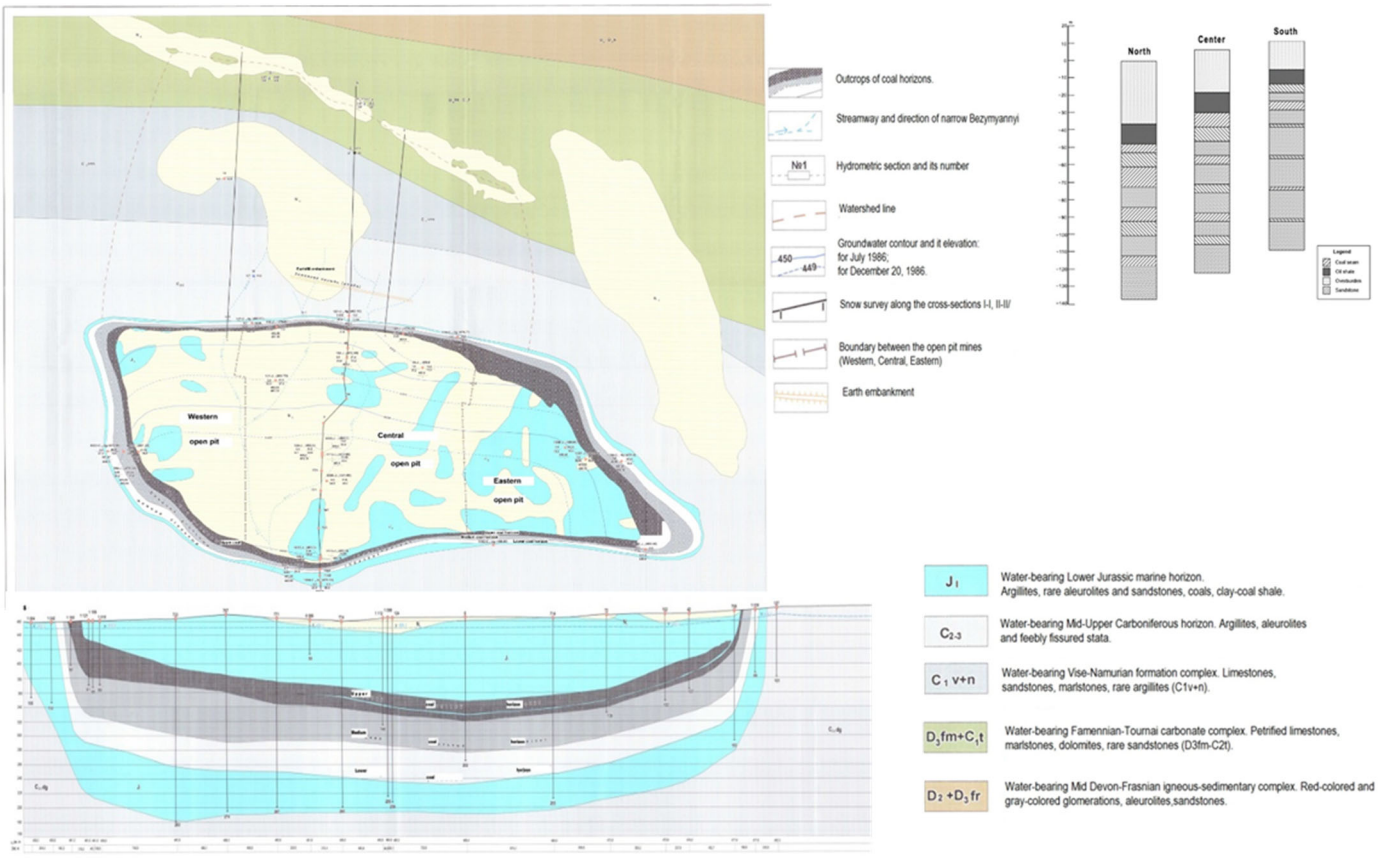

Figure A2. A generalized map and cross-sections for Shubarkol deposit [10,19].

References

1. Zholtaev, G.; Mussina, E.; Fazylov, M.M. The Tekes-Karkara sedimentary basin prospect assessment for identifying industrial oil shale deposits. *Geol. Miner. Resour. Prot.* **2020**, *75*, 4–10. (In Russian)
2. Speirs, J.; McGlade, C.; Slade, R. Uncertainty in the availability of natural resources: Fossil fuels, critical metals and biomass. *Energy Policy* **2015**, *87*, 654–664. [CrossRef]
3. Li, J.; Yang, Q.; Liu, Y.Q.; Ma, Y. Mapping of Petroleum and Minerals Reserves and Resources Classification Systems. In Proceedings of the International Field Exploration and Development Conference, Chengdu, China, 23–25 September 2020; pp. 3405–3416.
4. Dyni, J.R. Geology and Resources of Some World Oil-Shale Deposits. *Oil Shale* **2003**, *20*, 193–252. [CrossRef]
5. Sabanov, S.; Mukhamedyarova, Z. Prospectivity analysis of oil shales in Kazakhstan. *Oil Shale* **2020**, *37*, 269–280. [CrossRef]
6. Matheson, S.G.; Sorby, L.A. Proposals for the reporting of oil shale resources in Queensland, Australia. *Fuel* **1990**, *69*, 1073–1208. [CrossRef]
7. Sabanov, S.; Qureshi, A.R.; Dauitbay, Z.; Kurmangazy, G. A Method for the Modified Estimation of Oil Shale Mineable Reserves for Shale Oil Projects: A Case Study. *Energies* **2023**, *16*, 5853. [CrossRef]
8. Golitsyn, M.; Dumler, L.; Orlov, I. (Eds.) *Geology of Coal Fields and Shale Oil Deposits of the USSR*; Nedra: Moscow, Russia, 1973; Volume 5, Book 2. (In Russian)
9. Azizov, T.; Vlasov, Y. *Coal and Oil Shale Basins and Deposits of Kazakhstan*; AB Bekturov Institute of Chemical Sciences JSC: Almaty, Kazakhstan, 2013; pp. 6–106, The reference book compiled by Ministry of Geology and Mineral Protection of the Republic of Kazakhstan 1997.
10. Zelenin, N.I.; Ozerov, I.M. *Handbook on Oil Shales*; Nedra: Leningrad, Russia, 1983. (In Russian)
11. Gyulmaliev, A.M.; Kairbekov, Z.K.; Maloletnev, A.S.; Emel'yanova, V.S.; Maltykbaeva, Z.K. Thermodynamic analysis of the gasification of oil shale from the Kenderlyk deposit. *Solid Fuel Chem.* **2013**, *47*, 360–364. [CrossRef]
12. Tashmukhambetova, Z.K.; Kairbekov, Z.K.; Aubakirov, E.A.; Burkhanbekov, K.E.; Faizullaeva, M.F.; Shomanova, Z.K. Hydrogenation processing of carbon-containing wastes in a mixture with oil shale from the Kenderlyk deposit. *Solid Fuel Chem.* **2016**, *50*, 220–225. [CrossRef]

13. Kasenov, B.K.; Ermagambet, B.T.; Bekturganov, N.S.; Nabiev, M.A.; Kasenova, S.B.; Sagintaeva, Z.I.; Kuanyshbekov, E.E.; Seisenova, A.A. Chemical composition and heat capacity of shale from the Kendyrlyk and Shubarkol deposits. *Solid Fuel Chem.* **2016**, *50*, 149–151. [CrossRef]
14. Punanova, S.A.; Nukenov, D. The question of environmental consequences at horizontal drilling of shale formations in connection with their enrichment with microelements. *Georesources* **2017**, *19 Pt 1*, 239–248. [CrossRef]
15. Akhmetkarimova, Z.S.; Baikenov, M.I.; Meiramov, M.G.; Ordabaeva, A.T.; Khrupov, V.A.; Muldakhmetov, Z.H. Cleaning shale oil from phenol. *Chem. J. Kazakhstan* **2015**, *3*, 202–206.
16. Yermagambet, B.T.; Nurgaliyev, N.U.; Kassenova, Z.M.; Zikirina, A.M.; Abylgazina, L.D. Investigation of the thermal decomposition process of oil shale of the Shubarkol deposits. *Eur. Sci.* **2016**, *10*, 11–13. Available online: https://scientific-publication.com/h/sborniki/tekhnicheskie-nauki/262-issledovanie-protsessa-termicheskogo-razlozheniya.html (accessed on 7 November 2024).
17. Sapargaliyev, E. Geological and technological development prospects for Uralian oil shales as complex energetic raw materials. *Kazakh Natl. Acad. Nat. Sci. Her.* **2017**, *1*, 34–44.
18. Gilgenberg, A. *Shubarkol Deposit Mine Design*; Aivengo, L.C., Ed.; Ministry of Industry and Infrastructure Development of Kazakhstan: Astana, Kazakhstan, 2019; Volume 1, Book 1.
19. Arbuzov, V.A.; Zhaksybaeva, G.S.; Arbuz, G.S. *Shubarkol Oil Shale Pyrolysis Products Output Depending on Temperature*; Karaganda State Industrial University: Temirtau, Kazakhstan, 2014; Chapter 4; pp. 83–86, (In Russian). Available online: https://kgiu.kz/wp-content/uploads/2014/06/razdel-4_xim-texnologii_1.pdf (accessed on 30 October 2024).
20. Clark, C.E. The PERT model for the distribution of an activity. *Oper. Res.* **1962**, *10*, 405–406. [CrossRef]
21. Lambrigger, D.D.; Shevchenko, P.V.; Wuthrich, M.V. The quantification of operational risk using internal data, relevant external data and expert opinion. *J. Oper. Risk* **2007**, *2*, 3–27. [CrossRef]
22. Karwanski, M.; Grzybowska, U. Modeling Correlations in Operational Risk. *Acta Phys. Pol. A* **2018**, *133*, 1402–1407. [CrossRef]
23. Reinsalu, E.; Valgma, I.; Väli, E. Usage of Estonian Oil Shale. *Oil Shale* **2008**, *25*, 101–114.
24. Valgma, I.; Reinsalu, E.; Sabanov, S.; Karu, V. Quality Control of Oil Shale Production in Estonian Mines. *Oil Shale* **2010**, *27*, 239–249. [CrossRef]
25. Wang, L.; Zhao, Y.; Yang, D.; Kang, Z.; Zhao, J. Effect of pyrolysis on oil shale using superheated steam: A case study on the Fushun oil shale, China. *Fuel* **2019**, *253*, 1490–1498. [CrossRef]
26. Fowler, T.D.; Vinegar, H.J. Oil shale ICP-Colorado field pilots. In Proceedings of the SPE Western Regional Meeting, San Jose, CA, USA, 24–26 March 2009; SPE: Houston, TX, USA, 2009; p. SPE-12116. [CrossRef]
27. Brandt, A. Converting Oil Shale to Liquid Fuels: Energy Inputs and Greenhouse Gas Emissions of the Shell in Situ Conversion Process. *Environ. Sci. Technol.* **2008**, *42*, 7489–7495. [CrossRef]
28. Ryan, R.C.; Fowler, T.D.; Beer, G.L.; Nair, V. Shell's in situ conversion process—from laboratory to field pilots. In *Oil Shale: A Solution to the Liquid Fuel Dilemma*; American Chemical Society: Washington, DC, USA, 2010; pp. 161–183. [CrossRef]
29. Shi, Y.; Li, S.; Ma, Y.; Yue, C.; Shang, W.; Hu, H.; He, J. Pyrolysis of yaojie oil shale in a sanjiangtype pilot-scale retort. *Oil Shale* **2012**, *29*, 368. [CrossRef]
30. Crawford, P.; Biglarbigi, K.; Dammer, A.; Knaus, E. Advances in World Oil Shale Production Technologies. In Proceedings of the SPE Annual Technical Conference and Exhibition, Denver, CO, USA, 21–24 September 2008.
31. Opik, I.; Golubev, N.; Kaidalov, A.; Kann, J.; Elenurm, A. Current status of oil shale processing in solid heat carrier UTT (Galoter) retorts in Estonia. *Oil Shale* **2001**, *18*, 99–107. [CrossRef]
32. Elenurm, A.; Oja, V.; Tali, E.; Tearo, E.; Yanchilin, A. Thermal processing of dictyonema argillite and kukersite oil shale: Transformation and distribution of sulfur compounds in pilot-scale Galoter process. *Oil Shale* **2008**, *25*, 328–334. [CrossRef]
33. Neshumayev, D.; Tõnu Pihu, T.; Siirde, A.; Järvik, O.; Konist, A. Solid heat carrier oil shale retorting technology with integrated CFB technology. *Oil Shale* **2019**, *36*, 99–113. [CrossRef]
34. Gusca, J.; Siirde, A.; Eldermann, M. Energy related sustainability analysis of shale oil retorting technologies. *Energy Procedia* **2015**, *72*, 216–221. [CrossRef]
35. Kang, Z.; Zhao, Y.; Yang, D.; Tian, L.; Li, X. A pilot investigation of pyrolysis from oil and gas extraction from oil shale by in-situ superheated steam injection. *J. Pet. Sci. Eng.* **2020**, *186*, 106785. [CrossRef]
36. Kang, Z.; Zhao, Y.; Yang, D. Review of oil shale in-situ conversion technology. *Appl. Energy* **2020**, *269*, 115121. [CrossRef]
37. He, Y.G. Mining and utilization of Chinese Fushun oil shale. *Oil Shale* **2004**, *21*, 259–264. [CrossRef]
38. He, D.; Guan, J.; Hu, H.; Zhang, Q. Pyrolysis and co-pyrolysis of Chinese Longkou oil shale and Mongolian Huolinhe lignite. *Oil Shale* **2015**, *32*, 151. [CrossRef]
39. Qian, J.; Wang, J.; Li, S. Oil shale development in China. *Oil Shale* **2003**, *20* (Suppl. S3), 356–359. [CrossRef]
40. Pan, Y.; Zhang, X.; Liu, S.H.; Yang, S.C.; Ren, N. A review on technologies for oil shale surface retort. *J. Chem. Soc. Pak.* **2012**, *34*, 1331–1338. Available online: https://api.semanticscholar.org/CorpusID:67785496 (accessed on 26 January 2025).
41. Qian, J.; Wang, J. World oil shale retorting technologies. In Proceedings of the International Conference on Oil Shale: Recent Trends in Oil Shale, Amman, Jordan, 7–9 November 2006; pp. 7–9.

42. Samer, I.; Mohammed, O.J.; Azzam, O.J. Microwave-assisted solvent extraction of shale oil from Jordanian oil shale. *Oil Shale* **2015**, *32*, 240–251. Available online: https://api.semanticscholar.org/CorpusID:113605395 (accessed on 26 January 2025).
43. Wang, M.; Li, M.; Li, J.B.; Xu, L.; Zhang, J.X. The key parameter of shale oil resource evaluation: Oil content. *Pet. Sci.* **2022**, *19*, 1443–1459. [CrossRef]
44. Wang, J.X.; Sun, P.C.; Liu, Z.J.; Xu, Y.B.; Li, L. Evaluation of oil shale resources based on geochemistry and logging in Tuanyushan, Qaidam Basin, Northwest China. *Oil Shale* **2020**, *37*, 188. [CrossRef]
45. Jarvie, D.M. Total Organic Carbon (TOC) Analysis. In *AAPG Treatise of Petroleum Geology*; Merrill, R.K., Ed.; AAPG: Tulsa, OK, USA, 1991; pp. 113–118.
46. Jia, J.; Liu, Z.; Meng, Q.; Liu, R.; Sun, P.; Chen, Y. Quantitative evaluation of oil shale based on well log and 3-D seismic technique in the Songliao Basin, northeast China. *Oil Shale* **2012**, *29*, 128–150. [CrossRef]
47. Li, Y.; Sun, P.; Liu, Z.; Rong, L.; Li, Y.; Zhang, M. Characteristics of Upper Permian oil shale and analysis of the resource development potential in the Lucaogou Formation in the Junggar Basin, northern Bogda Mountains, Northwest China. *Oil Shale* **2020**, *37*, 207–223. [CrossRef]
48. Zhou, L.; Pang, X.; Wu, L.; Kuang, L.; Pang, H.; Jiang, F.; Bai, H.; Peng, J.; Pan, Z.; Zheng, D. Petroleum generation and expulsion in middle Permian Lucaogou Formation, Jimusar Sag, Junggar Basin, northwest China: Assessment of shale oil resource potential. *Geol. J.* **2017**, *52*, 1032–1048. [CrossRef]
49. Stupakova, A.V.; Kalmykov, G.A.; Fadeeva, N.P.; Bogomolov, A.K.; Kiryukhina, T.A.; Korobova, N.I.; Maltsev, V.V.; Pronina, N.V.; Sautkin, R.S.; Suslova, A.A.; et al. On the estimation of shale-oil resources and reserves. *Mosc. Univ. Geol. Bull.* **2015**, *70*, 183–190. [CrossRef]
50. Liu, C.; Zhao, W.; Sun, L.; Zhang, Y.; Chen, X.; Li, J. An improved ΔlogR model for evaluating organic matter abundance. *J. Pet. Sci. Eng.* **2021**, *206*, 109016. [CrossRef]
51. Liu, Z.; Meng, Q.; Dong, Q.; Zhu, J.; Guo, W.; Ye, S.; Liu, R.; Jia, J. Characteristics and resource potential of oil shale in China. *Oil Shale* **2017**, *34*, 15–41. [CrossRef]
52. Li, Q.; Chen, F.; Wu, S.; Zhang, L.; Wang, Y.; Xu, S. A simple and effective evaluation method for lacustrine shale oil based on mass balance calculation of Rock-Eval data. *Appl. Geochem.* **2022**, *140*, 105287. [CrossRef]
53. Zhang, X.; Li, Y.; Wang, Y. Calculation method of well controlled shale oil reserves based on Monte Carlo principle. In Proceedings of the Sixth International Conference on Advanced Electronic Materials, Computers, and Software Engineering (AEMCSE 2023), Shenyang, China, 21–23 April 2023; SPIE: Bellingham, WA, USA; Volume 12787, pp. 159–164. [CrossRef]
54. Wen, H.; Xiao, C.; Li, W.; Zhi, G. Application of Monte Carlo method in oil and gas reserves estimation. *J. Chengdu Univ. Technol.* **2002**, *29*, 487–492.

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