Development of Rare-Earth Elements Database for the East Kootenay Coalfield of Southeastern British Columbia (NTS 082G/10, 15) Using Field-Collected Samples: Updated Results

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Introduction

According of the International Union of Pure and Applied Chemistry (IUPAC), rare-earth elements (REEs) include 15 lanthanides plus Sc and Y (Connelly et al., 2005). They are grouped into two categories: light REEs (LREEs) and heavy REEs (HREEs). The elements La to Gd and Sc belong to the LREEs group and the HREEs group consists of Tb to Lu and Y (Moldoveanu and Papangelakis, 2013; Zhang et al., 2015). The REEs are used in the manufacturing of a wide variety of products and devices, such as light-emitting diodes, permanent magnets, catalytic converters, hybrid cars, wind turbines, fibre optics, super conductors and defence equipment (Balaram, 2019). China is one of the dominant suppliers of REEs globally and accounts for on average 86% of total rare-earth oxide production in the last 20 years (U.S. Geological Survey, 2021). The demand for REEs has increased significantly as the global transition to a low carbon economy has gained greater momentum in the recent years (Goodenough et al., 2018). The REEs are classified as critical elements in different studies due to increased supply risk to meet the future demand, considering various geopolitical, geological, environmental and market risks (U.S. Department of Energy, 2010; Deloitte Sustainability et al., 2017; Natural Resources Canada, 2020). To mitigate the supply risk, coal-related feedstocks are being evaluated as alternative sources of REEs for future exploitation (Seredin and Dai, 2012; Dai and Finkelman, 2018). The detailed review of REE occurrences and enrichment in coal deposits and geochemical analyses results are reported in the literature (Zhang et al., 2015; Dai et al., 2016). Using the U.S. Geological Survey's (USGS) coal database, the National Energy Technology Laboratory (NETL) in the United States has assessed coal deposits as source material for REE production (Bryan et al., 2015). As a result, NETL has funded a research and development program to demonstrate the techno-economic feasibility of developing domestic technologies to separate REEs from coal and/or its byproducts that contain a minimum of 300 ppm total REEs (U.S. Department of Energy, 2016).

Data indicating the presence of REEs in Canadian coal deposits scarcely exists, but some coal deposits have been studied for trace elements (Goodarzi, 1988; Birk and White, 1991; Goodarzi et al., 2009). There have been no efforts made to specifically quantify and characterize the REEs in British Columbia (BC) coal deposits or other coal deposits in Canada for subsequent extraction. The main objective of this study is to create a REE database for the East Kootenay coalfield (Figure 1) using field-collected samples to identify the best potential source material in the study area. A few samples in the database were also evaluated for extraction of REEs, using processes such as magnetic-, density- and gravity-based methods, flotation, ion-exchange and leaching. Preliminary results on the REE database were reported previously (Kuppusamy and Holuszko, 2021), and this database is now updated with additional field-collected samples and presented in this paper.

Materials and Methods

In 2020 and 2021, samples were collected by coal geologists from their respective mines to develop the database. Sample preparation in the lab was conducted in accordance with ASTM standards for coal sample preparation. A lithium-borate fusion was used in the REE analysis and four-acid digestion in the analysis for other minor elements. For a few reactive samples, aqua-regia digestion was adopted for minor element analyses. The digested solutions were analyzed by inductively coupled plasma–mass spectrometry (ICP-MS). All the chemical analyses reported in this study were conducted by ALS-Geochemistry (Vancouver, British Columbia). In this study, REEs in samples are expressed as follows: on a whole coal basis (REE concentra-

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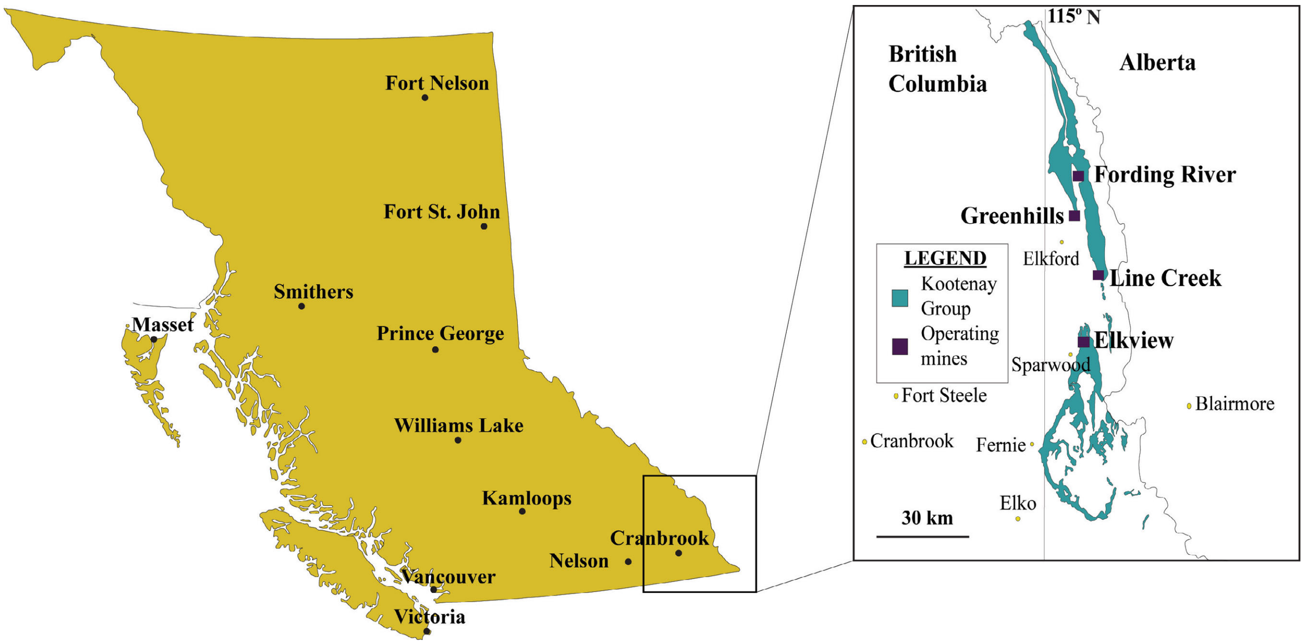

Figure 1. Location of East Kootenay coalfield and operating coal mines in southeastern British Columbia (adapted from BC Geological Survey, 2019).

tion in the coal sample) and on an ash basis (REE concentration in the ash of the coal sample). The procedure followed for sampling, preparation and chemical analyses is detailed in Kuppusamy and Holuszko (2021).

Results and Discussion

The preliminary results of 49 samples were reported previously (Kuppusamy and Holuszko, 2021). In this paper, the data is updated with an additional 55 samples collected from the study area. Results of the proximate analysis of 37 coal samples are shown in Table 1. According to ASTM D388-17 (2017), all the coal samples can be classified as low-to-medium volatile bituminous coal, which is of a metallurgical quality. For the database, more than 60 parameters were collected for each sample, including type, rank and major-, minor- and trace-elements concentrations. Once the study is completed, the comprehensive dataset will be released in future reports. Seam identification and the specific locations of the individual samples are not disclosed to uphold a confidentiality agreement.

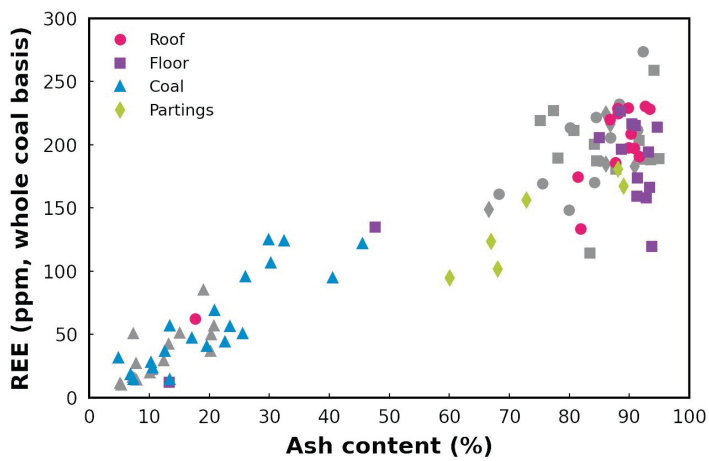

Figure 2. Rare-earth element (REE) concentration (on whole coal basis; ppm) versus ash content (%) for the roof, floor, coal and partings samples from the East Kootenay coalfield, southeastern British Columbia. Grey colour markers indicate data points reported last year.

The REE concentration in the samples varied from 91 to 686 ppm on ash basis and more than 77% of total REEs was accounted for by five elements (Ce, La, Nd, Y, Sc). The maximum, minimum and average REE concentrations on ash basis for different geological material collected, including roof, floor, coal and partings, are listed in Table 2. It can be observed that coal showed an enhanced concentration of REEs when compared to the other material types. As shown in Figure 2, the concentration of REEs increases with ash content of the material on a whole coal basis indicating the preferred REEs association with mineral matter, which is comparable with previously published results (Kuppusamy and Holuszko, 2021). On Figure 2, grey colour markers indicate data points reported last year. During the coal beneficiation process, the REEs associated with mineral matter are generally concentrated into waste tailings streams. The flotation of East Kootenay coal samples showed that most of the REEs by weight were reported to the middlings and tailings streams (Kuppusamy and Holuszko, 2019), which confirms the trend shown in Figure 2.

Table 1. Proximate analysis results for coal samples (as-determined basis) from the East Kootenay coalfield, southeastern British Columbia. Abbreviation: ID, identification.

Sample ID	Type	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)
10	Coal	2.41	7.24	22.85	67.5
11	Coal	2.81	10.12	21.92	65.14
12	Coal	2.39	7.66	23	66.95
13	Coal	2.41	7.52	22.92	67.14
14	Coal	2.43	7.93	23.02	66.62
15	Coal	2.5	10.46	22.3	64.74
16	Coal	2.62	5.1	24.08	68.2
17	Coal	2.1	5.29	23.69	68.93
18	Coal	2.09	20.24	27.29	50.38
19	Coal	2.75	7.37	25.68	64.2
20	Coal	1.36	12.39	24.67	61.59
22	Coal	0.85	19.05	19.39	60.71
26	Coal	1.25	7.84	22.73	68.19
27	Coal	1.24	13.19	19.32	66.26
41	Coal	1.31	20.74	23.11	54.84
48	Coal	0.66	20.34	20.15	58.85
49	Coal	0.87	15.06	22.16	61.91
53	Coal	1.03	10.57	24.32	64.08
54	Coal	1.36	6.87	28.70	63.07
60	Coal	1.39	10.32	30.69	57.61
61	Coal	1.00	30.27	22.78	45.94
69	Coal	0.77	32.47	20.68	46.08
73	Coal	0.62	12.58	22.80	64.00
74	Coal	0.60	20.89	24.46	54.05
76	Coal	0.62	25.98	21.75	51.65
78	Coal	0.46	7.36	22.29	69.89
81	Coal	1.97	29.88	19.68	48.46
83	Coal	1.51	45.55	18.00	34.94
87	Coal	1.21	4.86	5.57	88.35
89	Coal	1.07	13.37	14.18	71.38
96	Coal	1.03	40.52	15.51	42.94
98	Coal	0.74	13.40	18.39	67.47
99	Coal	0.86	23.48	18.40	57.26
100	Coal	0.75	22.64	22.12	54.50
102	Coal	0.55	19.53	22.57	57.35
103	Coal	0.97	25.60	24.66	48.77
104	Coal	0.94	17.10	26.21	55.75

The preliminary economic evaluation of samples was conducted using the evaluation plot proposed by Dai et al. (2017). In the plot, REE concentration was plotted against outlook coefficient (C_{outl}), which signifies the quality of REEs present in the sample. Using the plot, samples were grouped into three categories. An explanation of the REE cut-off grades and calculation of outlook coefficient can be found in Kuppusamy and Holuszko (2021). The evaluation plot was adopted to accommodate the resource cut-off suggested in U.S. Department of Energy (2016), which classifies the samples into five categories: unpromising source (REE <300 ppm on ash basis or C_{outl} <0.7); promising resource (300<REE<720 ppm on ash basis and 0.7<C_{outl}<2.4); highly promising resource (300<REE<720 ppm on ash basis and C_{outl}>2.4); promising source (REE >720 ppm on ash basis and 0.7<C_{outl}<2.4); and highly promising source (REE >720 ppm on ash basis and C_{outl} >2.4). All the samples in the REE database were plotted in the modified plot and are shown in Figure 3. The updated data points are shown in different colours, whereas last year's data points are shown in grey.

Table 2. Maximum, minimum and average rare-earth element (REE) concentrations (on ash basis; ppm) in the roof, floor, coal and partings samples from the East Kootenay coalfield, southeastern British Columbia.

Type	Maximum	Minimum	Average
Roof	351.3	163.1	238.4
Floor	293.3	90.8	216.2
Coal	685.9	105.1	284.3
Partings	260.4	149.5	204.3

Table 3. Maximum, minimum and average heavy rare-earth elements (HREEs) to light rare-earth elements (LREEs) ratio and outlook coefficient in the different coal sample types from East Kootenay coalfield, southeastern British Columbia.

Type	HREEs-LREEs			Outlook coefficient		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Roof	0.37	0.17	0.28	1.41	0.77	1.11
Floor	0.38	0.18	0.27	1.42	0.85	1.06
Coal	0.58	0.22	0.34	1.72	0.73	1.19
Partings	1.03	0.21	0.35	2.93	0.82	1.27

The C_{outl} values for most of the samples are >1, implying that the critical REE concentration is significant and accounts for, on average, 36% of the total REEs. Further, it can be noticed from Table 3 that HREE concentrations are generally more significantly concentrated in coal compared to roof, partings and floor samples, in some cases they consist of more than 50% of total LREEs, which contributes to the better C_{outl} values. The average C_{outl} for the coal samples is found to be 1.2, which is consistent with results from Kuppusamy and Holuszko (2021). Additionally, certain partings samples also showed enriched HREE concentrations, which resulted in the highest outlook coefficient observed among the tested samples. Because of HREE enrichment in some samples, the general statistics of partings were improved and comparable to that of coal values in terms of HREE-LREE ratio and outlook coefficient. Since the reported C_{outl} for world coal is 0.64 (Zhang et al., 2015; Dai et al., 2017), these results show that BC coals may become a viable source of REEs if extraction processes are further refined.

Correlation analysis also shows a strong correlation between coal ash and REE content (except Sc) when calcu-

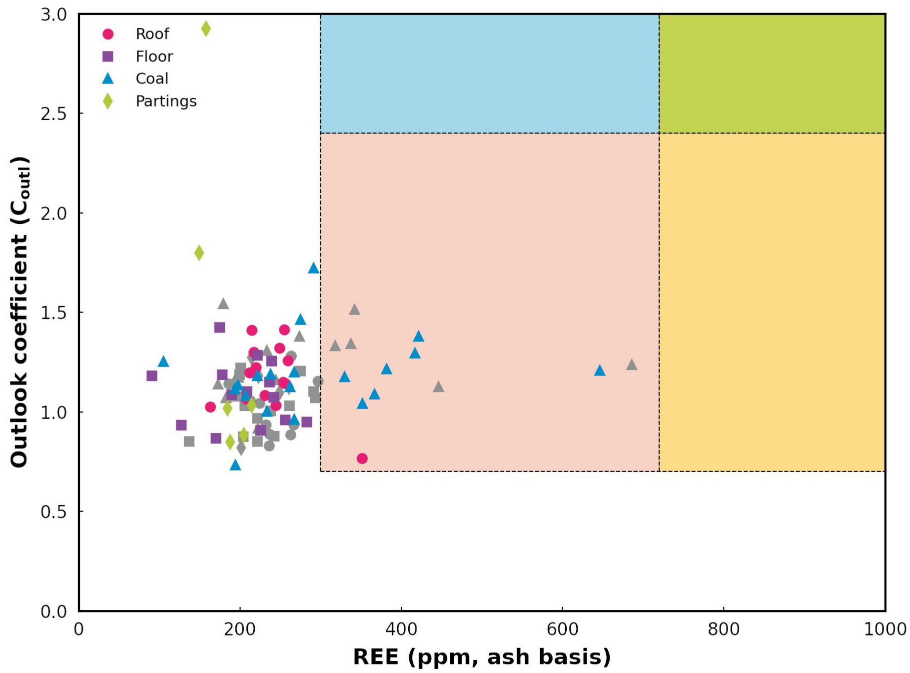

Figure 3. Outlook coefficient (C_{outl}) versus rare-earth element (REE) concentration for various types of coal samples from the East Kootenay coalfield, southeastern British Columbia. The REE resource categories for coal sources: green, highly promising source; yellow, promising source; blue, highly promising resource; light salmon, promising resource. Grey colour markers indicate data points reported last year.

lated on a whole coal basis (r = +0.86 to 0.93). This indicates the presence of various mineral phases containing REEs in the coal samples. One of the REE carriers in these types of metalliferous coal is zircon, which can originate from volcanic ash or authigenic minerals and it can be identified by enrichment of Hf, Th, U and HREEs (Finkelman, 1981; Seredin, 2004). A compelling correlation between Hf, Th, U, Y and other REEs implies that zircon could be one of the source minerals of REEs and indicates an input of volcanic ash containing REEs into these coals. Elemental analysis by ICP-MS indicated the presence of zirconium in these samples. Also, volcanic ash is believed to be the source of tonsteins associated with the coal beds in the Mist Mountain Formation in the East Kootenay coalfield (Grieve, 1993), which further validates the inference made in this study.

No correlation was observed between ash and REE content when calculated on an ash basis (r = –0.07 to 0.44). This implies that only a small amount of REEs is associated with organic matter in the studied samples. To confirm this, the next step would be to look for a strong correlation between REEs and W, which is believed to be organically fixed in coal. However, a very weak correlation was shown between REE and W in the studied samples (r = +0.14 to 0.37) indicating inorganically associated REEs.

In the samples, on the whole coal basis, REEs strongly correlated with U (r >+0.84) and Th (r >+0.80). This suggests that one of the REE mineral phases could be monazite, but a more detailed mineralogical study is required to confirm its presence in the sample.

The modified evaluation plot was used to select a few samples with a high potential for use as REE feedstock. These select few samples are currently being investigated to understand the mode of occurrence and REE mineralogy. Further, REE extraction potential from these samples is also being assessed using bench-scale test works. The final report containing the entire database, characterization and extraction study results will be published in the near future.

Conclusions

In this study, more than 100 samples were collected from the East Kootenay coalfield to develop a rare-earth element (REE) database for the study area. The results from the first 49 samples were reported previously and the database is now being updated with an additional 55 samples. It was found that total REE concentrations on ash basis varied from 91 to 686 ppm. Considering different geological material types, the tested coal samples showed enriched REE concentrations. Further, the concentrations of heavy rare-earth elements (HREEs) were generally higher in coal and partings samples. In certain partings samples, the HREE–light rare-earth element (LREE) ratio was >1 meaning the concentration of HREEs was greater than the LREEs, which was reflected in the significantly higher outlook coefficient value, showing increased economic potential.

Further, correlation analysis revealed a significant domination of inorganic association of REEs in the samples.

The extraction of REEs from alternative source material is currently being developed for successful exploitation of these resources. Even though REE concentration in coal sources are considerably lower than conventional REE deposits, the extraction of REEs from coal-based feedstocks has numerous advantages compared to traditional REE mining, including reduced cost, environmental footprint and waste management. Further, coal-based source material was also shown to contain other valuable elements such as Ge, Ga, Li, V, Nb Au, Ag, Al and platinum group elements, which can also be co-extracted with REEs paving the way for more sustainable resource usage.

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