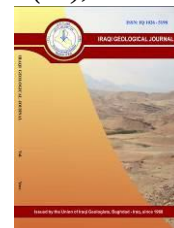




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Characterization of Mineral and Maceral Phases Containing Rare Earth Elements Found in Balikpapan and Pulau Balang Formations Coal Seams

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Abstract

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Modern technologies depend on rare earth elements, however, their supply is limited, hence research into substitute sources like coal and coal ash is required. In this study, coal ash specimens from the Balikpapan Formation and Pulau Balang Formation (FM.P. Balang) in the Kutai Basin, East Kalimantan, are analyzed for the Rare earth elements concentrations. X-ray fluorescence, petrographic analysis, proximal and ultimate analysis, and inductively coupled plasma optical emission spectrometry were the laboratory procedures conducted for this study. The results show considerable compositional differences among formations: low ash levels were found in Balikpapan Formation samples (2.30-2.47%), low sulfur ($\leq 0.15\%$), and high fixed carbon ($\sim 45.2\%$), unlike the samples in FM.P. Balang, it has higher ash (10.81-11.16%), increased sulfur (3.68-4.64%), and lower fixed carbon (~ 36.4 -37.1%). Analysis by X-ray fluorescence provides data showing FM contains 4.22-5.18% Fe_2O_3 . BPN and 10.60-14.20% in FM. P. Balang, SO_3 ranged from 1.2% to 17.1%. Rare earth elements analyses indicate similar, but much higher enrichment for La (18.30–24.32 ppm), Ce (28.88–42.19 ppm), Nd (38.50–51.45 ppm) and Y (29.70–33.54 ppm), for the Pulau Balang Formation compared to FM by factors of 2-3 times [120]. Quite a lot of BPN concentration values were found (La: 6.14-8.61 ppm; Ce: 4.21-12.66 ppm; Nd: 8.76-12.66 and Y: 50-7 mmole). Light Rare earth elements are more abundant than heavy Rare earth elements in all the samples while FM has only few detectable heavy Rare earth elements P. Balang GTR-2 (e. g. Dy 5.00 ppm, Er 5.28 ppm). These findings suggest that coal ash from the Kutai Basin, Mostly from the Pulau Balang Formation, is a good source for the extraction of Rare earth elements but at the same time the high content of sulfur and iron poses environmental problems.

Keywords: Maceral; Mineral; Rare earth elements; Balikpapan and Pulau Balang formations; Coal seam

1. Introduction

Rare earth elements (REE) are 17 elements found in the periodic table that have similar chemical and physical properties (Balaram, 2019). This group includes the lanthanide series, as well as yttrium and scandium (Wang et al., 2011; Seredin and Dia, 2012). According to Seredin and Dai (2012), REEs are considered the "cornerstone" of modern technology due to their unique magnetic, metallurgical,

electrochemical, phosphorescent, and catalytic properties (OECD, 2015; Balaram, 2019). With the ongoing development of new and advanced technologies in sectors such as electronics, clean energy, defense, optics, automotive, medicine, and agriculture, the rising demand for these elements has prompted investigations into alternative sources of REE (Balaram, 2019).

The European Commission's 2020 Report of the Raw Materials Supply Group identified REE as critical materials. REE are identified as critical materials in the 2020 Report of the Raw Materials Supply Group by the European Commission. These metals are categorized as essential due to four factors: 1) geological scarcity, 2) potential supply constraints, 3) elevated prices and 4) economic significance stemming from unique, challenging to replace properties (Ayres, 2013). These metals are categorized as essential due to several factors: 1) their geological scarcity; 2) the potential for supply constraints; 3) their elevated prices; and 4) their economic significance stemming from unique properties that are challenging to replace (Ayres, 2013). Bourzac (2011) asserted that the global community is facing an economic crisis regarding REEs availability. Over time, the supply has decreased, and export limitations and rising prices have intensified as China seeks to limit the export of specific critical raw materials. This has intensified the pressure on the worldwide supply (OECD, 2015; Taggart et al., 2016; Baron, 2020).

In the search for alternative sources of REE, coal and coal ash have been identified as potential alternative sources (Seredin and Dia, 2012; Taggart et al., 2016; USGS, 2019; Baron, 2020). Several authors (Seredin and Finkelman, 2008; Seredin and Dia, 2012; Taggart et al., 2016; Hower et al., 2016; USGS, 2019) had identified coal deposits as a potential source of critical and valuable elements including germanium, gallium, gold, niobium, platinum group elements, REE, rhenium, selenium, silver, uranium, and vanadium. Rare earth-bearing minerals found in coal include, but not limited to, zircon, crandallite, florencite, apatite, monazite, xenotime, bastnaesite, kimuraite, lanthanite, rhabdophane, cherchite, and rare earth oxides (Seredin and Dai, 2012; Dai et al., 2018; Ji et al., 2022). The most common rare earth-bearing minerals are phosphate minerals such as monazite and xenotime (Seredin and Dai, 2012; Finkelman et al., 1990; Rozelle et al., 2019; Yang et al., 2019). Various authors had reported that REEs and other elements are significantly enriched in coal during peat accumulation and coalification (Seredin and Dai, 2012; Wang et al., 2019; Zhao et al., 2019; Xie et al., 2021).

After coal is burned, minerals containing REEs remain in the coal ash because they are thermally stable and have low volatility (Wang et al., 2019; Zhao et al., 2019; Liu et al., 2019; Xie et al., 2021). These byproducts, collectively termed coal ash, are solid waste generated when coal is burned at approximately 1200 °C in coal-fired power plants to produce electricity. Coal ash consists of fly and bottom ash (Pan et al., 2020; Ritchie and Rosado, 2022). Coal ash is composed of organic components (such as unburned carbon, organic minerals, and char), inorganic elements (including amorphous matter, mineral matter, and mineral aggregates), and fluid constituents (including moisture and gases) (Vassilev et al., 2007; Saikia et al., 2015; Hower et al., 2017; Anggara et al., 2021). A significant amount of ash exists in an amorphous glassy state (Kelmers et al., 1982; Bryers, 1986; Dai et al., 2014; Kolker et al., 2017; Hower et al., 2017; Cao et al., 2018; USGS, 2019). According to Blissett and Rowson (2012) and Cao et al. (2018), the potential of coal ash as an alternative source of valuable materials, including rare earth elements, remains largely untapped. Similar to coal, coal ash is also recognized for containing critical metals (Ruhl et al., 2009; Ruhl et al., 2010; Dai et al., 2018; Tang et al., 2019).

It is economically beneficial to ascertain the concentration of REE, particularly essential REEs in coal ash. The average concentration of rare earth elements (REEs, based on whole coal) in coals from around the world is estimated as 68.5 parts per million (ppm), but reaches approximately 445 ppm in ash (Ketris et al., 2009). This trend has been confirmed by several investigations (Seredin and Dai, 2012; Hower et al., 2016; Franus et al., 2015; Santos et al., 2022) indicating that coal ash can have three times the REE concentrations in relation to UCC. Wagner and Matiane (2018) reported total REE concentrations in the ashes of equivalent power plants which were values from 488.9 to 598.7 ppm, but

for some South African coals, total REE ranged from 121 to up to about 124–150 ppm (whole coal). All of these values are higher than 445 ppm, the global average of coal-derived ash (Ketris et al., 2009). A better understanding towards the distributions of REEs in various coal ashes from Kutai Basin, East Kalimantan (Indonesia) received from this study. Aluminosilicate glassy phase may be reduced during the preparation of laboratory-derived low-temperature ash, increasing the possibility of REE extraction. The samples' maceral and mineral phases were identified using petrographic analysis. Meanwhile, the total REE content was determined by using inductively coupled plasma optical emission spectroscopy (ICP-OES). This study is considered as the first report on minerals and phases including rare earth elements in coal ash from the Kutai Basin.

This study has purpose to determine the mineral and maceral compositions of coal in the Pulau Balang and Balikpapan formations according to the characteristics of the coal layers. Subsequently, the rare earth metal content of the coal samples was analyzed. These results will have implications for the organic materials that constitute coal, specifically the maceral content.

2. Materials and Methods

The original source of these samples was the Kutai Basin coals, which were obtained from various formations, including three from the Balikpapan Formation (FM.BPN) and two from the Pulau Balang Formation (FM.P. Balang). The processes and procedures used in collecting the 2 kg samples provided are also relevant. The sampling location is shown in Fig. 1.

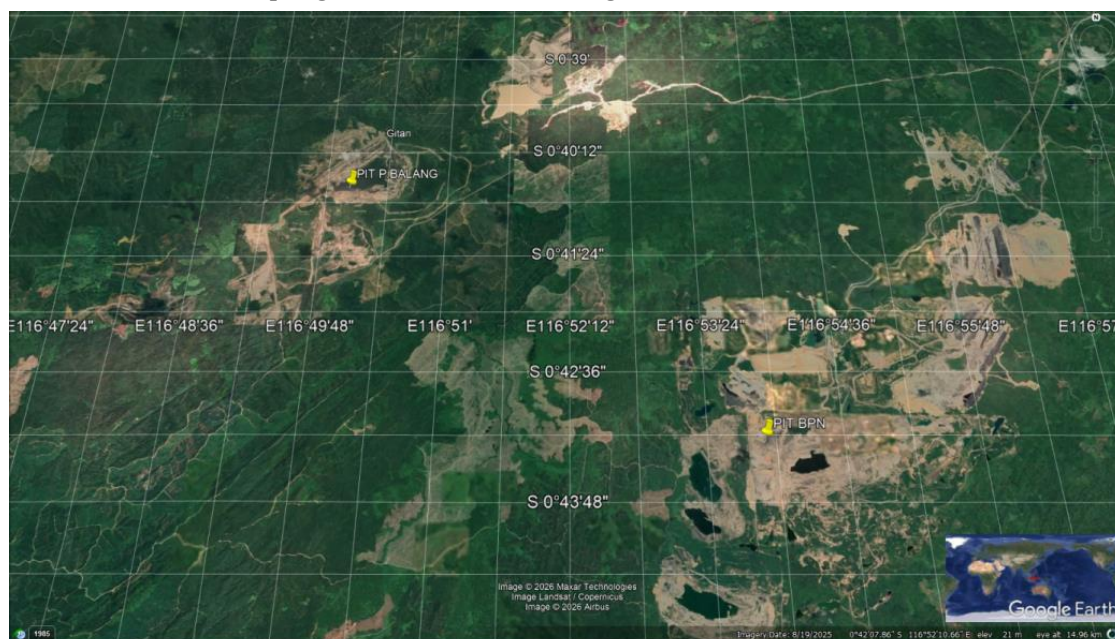


Fig. 1. Sampling location map

FM.BPN and FM.P. Balang samples were obtained as fine powders, eliminating the need for additional crushing. The samples were sieved through a $-32\ \mu\text{m}$ sieve to guarantee uniformity in particle size, as this factor can influence the overall dissolution. Any oversized particles were milled and re-sieved to meet the $-32\ \mu\text{m}$ specification. The ash samples were partitioned into eight equal segments utilizing a rotary splitter to ensure representative splits for subsequent analyses. Four opposing portions were further divided into eight segments twice, yielding smaller portions of approximately 100 g each. A 10 g sample from each portion was analyzed by X-ray fluorescence (XRF). The remaining samples were allocated for extraction experiments, proximate and ultimate analysis, maceral petrographic analyses, and ICP-OES.

3. Results and Discussion

3.1. Proximate and Ultimate Analysis Results

The proximate analysis data indicate that moisture (Table 1) (free and total) volatile matter ash content and fixed carbon differs among all samples. Free moisture content(ar) has a value range from 2.25% to 6.47% with highest values in the FM. P. Balang PIT GTR-2 1—means they are subjected to extended surface water retention. Total moisture content (ar) is highest in FM. P. Balang PIT samples (at 24.20%) which can affect handling, storage and combustion performance. This study tested air-dry basis (adb) indicators for two groups of coal samples: FM.BPN PIT and FM.P. Balang PIT. The moisture content of FM.BPN PIT ranges from 13.77% to 14.52%, which is lower than the 18.95% to 19.04% moisture content of FM.P. Balang PIT. The volatile matter of all tested samples falls between 32.80% and 38.68%, a high level that makes these coal samples suitable for high-calorific value application scenarios. The ash content of the latter sample group ranges from 10.81% to 11.16%, far higher than the former group's ash content of less than 2.5%; this gap will lead to increased combustion residues and shortened service life of boilers. This study tested two groups of coal samples collected from coal mining pits. On an air-dried basis (adb), the fixed carbon content of the FM.BPN PIT coal samples was far higher than that of the FM.P. Balang PIT coal samples, while its total sulfur content was far lower than that of the latter. The FM.P. Balang PIT coal is a high-sulfur coal, which requires matching sulfur dioxide control measures when put into use.

This study measured the core elemental compositions of two types of dry ash-free (daf) coal samples: the FM.BPN PIT sample has a carbon content exceeding 74.90%, and the FM.P. Balang PIT GTR-2 sample has an approximate carbon content of 69.67%. The hydrogen content of both samples remains stable at 4.88-5.37%, and their nitrogen content only ranges from 1.36% to 1.58%. The two samples respectively meet the requirements for combustion, volatile matter release, and low-nitrogen emission. The total sulphur (by dry ash free basis (daf)) in FM stays low. BPN PIT (0.14–0.15%), but is significantly elevated in FM. Values for P. Balang PIT samples (5.26–6.61%) corroborated the proximate analysis values, suggesting an increased environmental cost of combustion without sulfur emission controls from burning this coal. The ratio between the ash, sulphur and carbon contents reflects the correlation of inorganic and organic components of coal. Higher ash content in FM. The higher percentage of mineral matter observed in P. Balang samples is commonly associated with a higher sulfur content since sulfide minerals such as pyrite are present in coal samples which include sub-bituminous, bituminous and anthracite grades (Farr et al., 2007). In contrast, FM contains a lower content of ash and sulfur. Higher BPN leads to a higher fixed carbon content meaning it is a cleaner coal (more organic material). The significance of such an inverse relationship illustrates the affect that depositional environment and diagenetic processes have on coal composition.

Table 1. The Results of Proximate and Ultimate Analysis

Parameter	FM.BPN PIT SST-1	FM.BPN PIT SST-2	FM.BPN PIT SST-3	FM.P. Balang PIT GTR-1	FM.P. Balang PIT GTR-2
Proximate analysis (%)					
Moisture	14.52	13.77	13.99	19.04	18.95
Volatile matter	37.98	38.68	38.42	33.74	32.8
Ash	2.47	2.3	2.39	10.81	11.16
Fixed Carbon	45.03	45.25	45.2	36.41	37.09
Total Sulfur	0.13	0.13	0.12	4.64	3.68
Ultimate analysis (%)					
Carbon	74.96	74.93	75.2	70.57	69.67
Hydrogen	5.26	5.37	4.88	4.96	4.97
Nitrogen	1.58	1.5	1.55	1.37	1.36
Sulfur	0.15	0.15	0.14	6.61	5.26

In general, this kind of quantitative compositional insights that can facilitate an effective coal resource allocation strategy while ensuring the rational emission management and optimal industrial process selection are essential for mining engineering and energy production research. The differences in ash, sulfur and carbon contents are due to the changes in composition of inorganic mineral matter and organic parts of coal. FM contained a very high ash level. The rise in total sulfur and reduction in organic carbon (as C) in P. Balang samples indicate significant quantities of inorganic compounds as these were accompanied by the highest levels of sulfide minerals like pyrite. The FM. Though, the BPN samples contain lower ash and sulfur content but a larger proportion of fixed carbon, which indicates a low-polluting coal with a higher content of organic material. The relationship between ash and carbon content emphasizes the effect of depositional environment and post-depositional diagenetic processes. The increased mineral content in FM.P. Balang proposes that the enrichment of inorganic phases was caused by a greater detrital input or maritime effect during peat formation.

3.2. X-Ray Fluorescence Analysis Results

Table 2's XRF analytical results show that FM.BPN PIT and FM have significantly different inorganic elemental compositions. PIT coal samples from P. Balang. These information is crucial for comprehending the distribution of mineral matter and how it could affect environmental, processing, and usage aspects.

Table 2. The results of X-Ray fluorescence analysis

Oxide	FM.BPN PIT SST-1	FM.BPN PIT SST-2	FM.BPN PIT SST-3	FM.P. Balang PIT GTR-1	FM.P. Balang PIT GTR-2
SiO ₂	0.64%	0.40%	0.34%	5.51%	6.31%
Al ₂ O ₃	0.54%	0.35%	0.32%	2.85%	3.10%
Fe ₂ O ₃	4.22%	4.78%	5.18%	14.20%	10.60%
MgO	0.26%	0.24%	0.20%	0.54%	0.50%
CaO	4.46%	3.77%	3.84%	2.82%	2.93%
Na ₂ O	0.31%	0.32%	0.33%	256 ppm	<LLD
K ₂ O	406 ppm	330 ppm	336 ppm	0.44%	0.55%
TiO ₂	<LLD	<LLD	265 ppm	0.14%	0.19%
P ₂ O ₅	<LLD	<LLD	<LLD	<LLD	<LLD
MnO	102 ppm	151 ppm	<LLD	82.6 ppm	80.5 ppm
SO ₃	1.19%	1.28%	1.20%	17.10%	15.00%

The FM.BPN PIT samples have low SiO₂ (0.34–0.64%), Al₂O₃ (0.32–0.54%), MgO (0.20–0.26%), and CaO (3.77–4.46%) and show low amounts of silicate and aluminosilicate minerals. The FM.P. Balang PIT samples have significantly higher SiO₂ (5.51–6.31%), Al₂O₃ (2.85–3.10%), and MgO (0.50–0.54%), which may be related to an increased amount of quartz, clay minerals, and magnesian compounds. The high CaO values in all samples indicate the presence of substantial amounts of calcite or other carbonate minerals.

A significant difference was identified for Fe₂O₃. FM.BPN PIT samples reported values of 4.22% - 5.18%. Contrastingly, values of FM.P. Balang PIT increased to the range 10.60 – 14.20%. This can indicate an increase in the mineralization of iron possibly due to the presence of pyrite, siderite or any other iron-bearing minerals suggesting a significant influence on both the pre-combustion/post-combustion residue chemistry and combustion residue.

Sodium (Na₂O) and potassium (K₂O) are found at moderate levels, with FM.BPN PIT samples showing higher potassium (330–406 ppm) than FM.P. Balang PIT (256 ppm and 0.55%). TiO₂ is absent in FM.BPN PIT and present in FM.P. Balang PIT (0.14–0.19%), which may suggest the presence of

anatase or rutile. In all samples, P_2O_5 is below the lower limit of detection (LLD), so there are hardly any phosphate minerals. Results also indicate that there are variable levels of Manganese (MnO), where FM.BPN PIT SST-1 and SST-2 range from 102–151 ppm and samples from FM.P. Balang PIT are around 80 ppm. This shows that Mn minerals are only present in trace levels.

What's notable here is the very high SO_3 levels in FM.P. Balang PIT samples (15.00–17.10%), compared to FM.BPN PIT samples ($SO_3 < 1.3\%$). This is a case of sulfur enrichment similar to what has been documented, which shows that the use of such samples would require stringent controls. FM.P. Balang samples show a higher sulfur content of (18.95–19.04%) compared to FM.BPN samples (13.77–14.52%). This also indicates the presence of relatively high, either inherent or absorbed, moisture content in FM.P. Balang samples. FM.BPN samples also show an observed loss on ignition close to 97.7%, compared to FM.P. Balang samples which are close to 90%, indicating a higher content of FM.BPN samples and a higher content of FM.P. Balang samples.

The variations in elemental and mineralogic composition between FM.BPN PIT coals and FM.P. Balang PIT Coals significantly influence ash production, slagging potential, emissions, and processing methods. Because the FM.P. Balang PIT Coals contain elevated iron and sulphur levels, there will be a need to utilize remediation technologies to be used in the industrial processes employing them, while the higher silicate and aluminium levels in the FM.P. Balang PIT Coals will require consideration of ash fusion characteristics. The high sulphur and iron concentrations in the FM.P. Balang Formation pose a significant threat to the environment. The high levels of sulphur found primarily in the form of pyrite, will result in acid mine drainage (AMD) when exposed to air and water, producing sulphuric acids that will then carry toxic heavy metals within the surrounding areas. Coal combustion at high levels of sulfur will generate large amounts of sulfur dioxide (SO_2). The SO_2 is a primary contributor to poor air quality (air pollution) and to acid rain. The presence of iron greatly accelerates the oxidation reactions that damage the environment. Therefore, effective mitigation strategies (e.g., dulsification and emission control technologies) are necessary for sustainable use of these natural resources. Detailed XRF profiles provide the base information needed to optimize coal choice, treatment, and to assist in environmental management of resource engineering applications.

3.3. Maceral in Coal

The maceral in coal is the main organic component of coal that originates from the remains of ancient plants. Maceral in coal has a similar function to the minerals in inorganic rocks. Formed through the processes of reclamation (peat) and carbonization (coalification), their properties and types greatly affect coal's quality and characteristics. Maceral types are generally divided into three main groups: vitrinite, which originates from plant wood tissue and cellulose and generally dominates coal. Vitrinite greatly affects the calorific value, reflectance, and rank of coal. Liptinite is derived from parts of plants that are rich in volatile substances, such as spores, cuticles, resins, and waxes. It contains a high hydrogen content and plays an important role in producing liquid hydrocarbons during pyrolysis. Inertinite originates from plant residues that have oxidized or burned partially. Rich in carbon but poor in volatile substances, it is harder, more reflective, and less reactive than vitrinite. Fig. 2 shows the macerals vitrinite, liptinite, and inertinite.

The maceral composition of the coal samples from the Kutai Basin shows distinct differences between the Balikpapan (FM.BPN) and Pulau Balang (FM.P. Balang) formations (Table 3). Vitrinite is the dominant maceral group in all samples, ranging from 73.2–76.8% in FM.BPN and slightly lower from 72 to 73%, in FM.P. Balang. The liptinite content is higher in FM.BPN (11.0–17.6%) but decreases significantly in the FM.BPN (3.2–4.0%) indicates a reduced contribution of hydrogen-rich components in the latter.

Inertinite shows moderate variability, with values between 3.6 and 11.8% in FM.BPN, and 7 and 11.8% in FM.P. Balang. The most notable difference lies in the mineral matter content, which is very low in FM.BPN (<1%) but much higher in FM.P. Balang (11.2–17.8%).

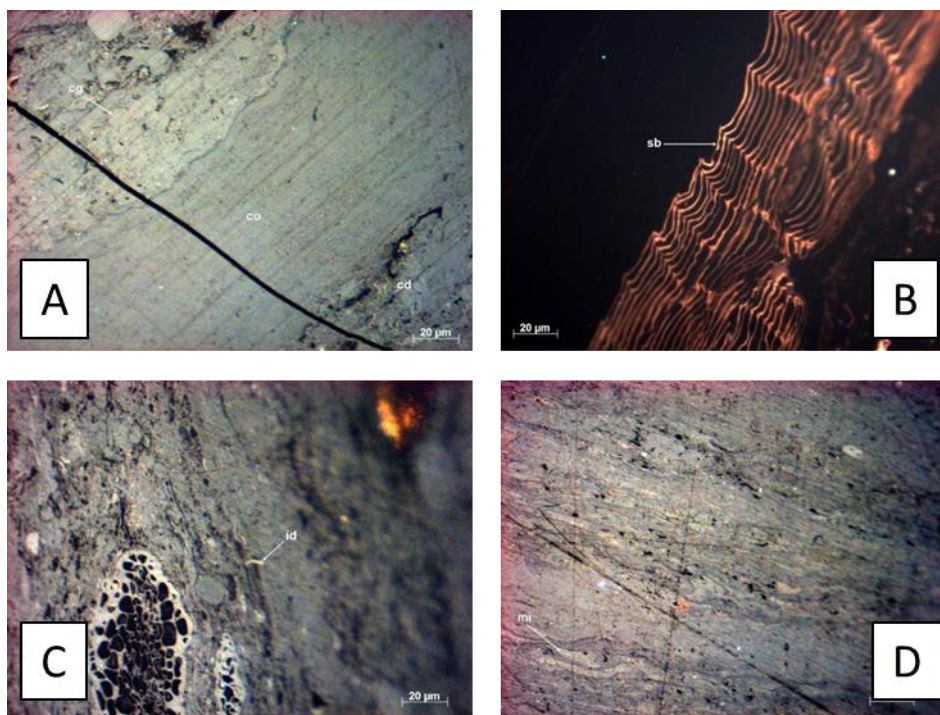


Fig. 2. Results of maceral petrographic analysis (A and D: Vitrinite maceral, B: Liptinite maceral, C: Inertinite maceral)

The differences between the samples are indicative of the chemical and physical processes that took place in their areas of deposition. For instance, the coal from FM.BPN is more organic and has a higher purity level when compared to the coal from FM.P. Balang, which has a higher concentration of mineralization. As a result, the combustion characteristics and REE potential of these two groups are different due to their differing amounts of vitrinite (highly developed organic structure) and liptinite (less developed organic structure). Looking at Table 4, there is a much higher amount of vitrinite and liptinite in FM.BPN than there is in FM.P. Balang, while there is a much higher amount of mineral matter present in FM.P. Balang.

Table 3. The Maceral Group Composition

Maceral Group	FM.BPN PIT SST-1	FM.BPN PIT SST-2	FM.BPN PIT SST-3	FM.P. Balang PIT GTR-1	FM.P. Balang PIT GTR-2
Vitrinite (%)	73.2	76.8	74.8	72	73
Liptinite (%)	16.6	11	17.2	3.2	4
Inertinite (%)	9.6	11.8	7.8	7	11.8
Mineral matter (%)	0.6	0.4	0.2	17.8	11.2

3.4. Minerals in Coal

Mineral data are reported in Table 4. Both FM.BPN and FM.P. Balang have mineral content differences that are quite large for both samples. The FM.P. Balang has a greater amount of mineral material than the FM.BPN but the mineral content for the FM.P. Balang is much more uniform than for the FM.BPN. There are also some unique minerals (like rutile and zircon) present in the samples of

FM.BPN that are not found in the samples of FM.P. Balang. The predominant mineral of FM.P. Balang is pyrite, whereas quartz is the dominant mineral of FM.BPN.

Table 4. The Mineral matter composition

Mineral	FM.BPN PIT SST-1	FM.BPN PIT SST-2	FM.BPN PIT SST-3	FM.P. Balang PIT GTR-1	FM.P. Balang PIT GTR-2
	%				
Quartz	0.0532	0.0330	0.0393	0.4900	1.4870
Alkali Feldspar	0.0110	0.0052	0.0006	0.4900	0.9700
Plagioclase	0.0087	0.0021	0.0005	0.1000	0.2960
Muscovite	0.0066	0.0017	0.0001	0.1900	0.9600
Kaolinite (Halloysite, Dickite)	0.0086	0.0085	0.0013	0.4000	1.0650
Chlorite	0.0000	0.0000	0.0001	0.0000	0.0000
Pyroxene	0.0000	0.0000	0.0003	0.0000	0.0010
Olivine	0.0002	0.0000	0.0000	0.0000	0.0000
Zircon	0.0000	0.0002	0.0002	0.0000	0.0000
Calcite	0.0001	0.0031	0.0014	0.0100	0.0000
Dolomite-Ankerite	0.0000	0.0000	0.0003	0.0000	0.0000
Apatite	0.0001	0.0000	0.0000	0.0000	0.0000
Pyrite	0.0002	0.0000	0.0001	11.3600	8.0350
Pyrrhotite	0.0001	0.0000	0.0000	0.5900	0.4580
Iron Spinel	0.0006	0.0001	0.0002	0.0600	0.0490
Rutile	0.0001	0.0001	0.0001	0.0000	0.0000

Mineral content in coals is a key factor in determining their overall quality/reaction/behaviour when combusted or converted. The table provided identifies a mix of silicates, carbonates, and sulphides, with nearly all of the mineral matter being unclassified (maseral). The most common minerals found in each coal sample were quartz, kaolinite (generally a clay-type mineral), feldspar, calcite, pyrite and (somewhat less commonly) large amounts of pyrrhotite + Fe-spinel in selected samples (Ward, 2016).

Various studies have indicated that quartz and clay minerals (primarily kaolinite and muscovite) are predominant mineral phases in the mineral content of coal. They are generally deposited as detrital material through the accumulation of organic matter forming peat and from post-depositional authigenic diagenetic processes. Recent studies have shown that kaolinite is often the most abundant mineral fraction, occurring in massive aggregates, thin flakes, or as cell fillings within the coal macerals. Pyrite, a sulfide mineral, is widely recognized and occurs in several forms, such as massive, framboidal, disseminated, and cell-filling forms, often linked to redox conditions and the presence of seawater during peat accumulation (Kostova et al., 1996; Dai and Chou, 2007; Matjie et al., 2016; Spears and Martinez-Tarazona, 2021; Zhang et al., 2025).

Comparative studies reveal that mineral matter content measured by low-temperature oxygen-plasma ashing normally is higher than the ash content obtained by the conventional proximate analysis. This happens because certain clay and carbonate minerals are volatilized or transformed through high-temperature decomposition. Such a difference has a great significance when one is interpreting the overall mineralogy and its effects on coal use (Matjie et al. 2016; Ward, 2016).

Mineral matter in coal affects many aspects of coal performance, like how much ash and slag are produced, the amount of sulfur emitted, and even the release or gathering of trace elements during use. Generally, alumina-silicate part of the ash can be ascribed to kaolinite and quartz. Though, pyrite is the major source of sulfur emission and the formation of acid gases. The size distribution of pyrite

particles and their association with macerals determine their combustion transformation paths, which is in line with the findings of Dai and Chou (2007), and Yang et al. (2021).

The difference in mineral components, for example a very high content of pyrite in some samples and the common characteristic of kaolinite in other cases, represent the different layers of coal seams, which have already been verified by various methods, like petrographic analyses, XRD, and plasma ashing. Research on this topic has been carried out in coalfields around the world. Global studies on coalfields (Matjie et al. 2016) have clearly reveal, an assemblage of clay minerals and pyrite, with quartz, calcite, and other minor constituents as accessory.

Such coal samples exhibit the usual diversity of minerals characteristic of terrestrial coals, which is in agreement with the very recent results obtained in coalfields of different parts of the world. The predominance of kaolinite and quartz, together with pyrite and carbonate phases, clearly demonstrates the pivotal role of these minerals in the characterization of coal resources and in the planning of their future utilization. Multi-technique approaches are recommended for the future studies to provide more reliable mineral quantification, understanding of ash behavior, release of trace elements, and environmental impact considerations.

3.5. Rare Earth Elements in Coal Samples

As Table 5 shows, the REE distribution in the coal samples varies widely both among elements and between locations.

Table 5. The Rare Earth Elements (ppm) Composition

Elements	FM.BPN PIT SST-1	FM.BPN PIT SST-2	FM.BPN PIT SST-3	FM.P. Balang PIT GTR-1	FM.P. Balang PIT GTR-2	UCC
La	8.61	6.44	6.14	18.30	24.32	30.0
Ce	12.66	7.22	4.21	28.88	42.19	34.0
Pr	35.73	32.89	34.38	28.84	22.10	7.1
Nd	12.66	10.93	8.76	38.50	51.45	26.0
Sm	7.38	5.98	6.29	9.51	9.16	4.6
Eu	<0.010	<0.010	<0.010	<0.010	2.24	0.9
Gd	19.26	19.68	21.42	31.48	31.35	3.8
Tb	2.96	3.46	3.13	6.51	5.16	0.6
Dy	<0.010	<0.010	<0.010	4.35	5.00	3.5
Ho	<0.010	<0.010	<0.010	<0.010	<0.010	0.8
Er	2.42	2.08	2.20	4.50	5.28	2.3
Tm	<0.010	<0.010	<0.010	<0.010	<0.010	0.3
Y	7.58	5.64	5.02	29.70	33.54	22.0
Yb	1.93	1.86	1.82	4.99	5.12	2.2
Lu	2.82	3.25	3.53	5.71	4.27	0.3
Sc	9.87	7.63	7.39	23.11	28.45	14.0
Total	123.88	107.06	104.29	234.38	269.63	152.39
Light REE	77.04	63.46	59.78	124.03	149.22	101.7
Medium REE	29.8	28.78	29.57	72.04	77.29	30.74
High REE	7.17	7.19	7.55	15.2	14.67	5.95

Generally, all sampling pits show higher concentrations of light REEs (LREEs) than heavy REEs (HREEs), such as La, Ce, Pr, Nd, and Sm and Dy, Ho, Er, Tm, Yb, and Lu. The FM.P.Balang PIT GTR-2 sample recorded the highest LREE concentration, with La and Ce dominant at 24.32 and 42.19 ppm, respectively. This also exhibits a diffuse distribution in FM.P.Balang PIT GTR-1 (La: 18.3 ppm, Ce:

28.88 ppm), indicating enrichment compared to FM.BPN PIT SST-1–3, where La and Ce are between 6.14–8.61 ppm and 4.21–12.66 ppm, respectively.

HREEs, including Dy, Ho, Er, and Tm in all FM.BPN PIT SST samples and FM.P.Balang PIT GTR-1, were generally below detectable limits (<0.010 ppm) but were moderately detectable in FM.P.Balang PIT GTR-2 (Er: 5.28 ppm, Dy: 5.00 ppm). Yttrium exhibits a relatively high value in FM.P.Balang PIT samples, especially in GTR-2, which amounts to 33.54 ppm, far higher than in FM.BPN PIT SST subsets.

Most of the coal samples from both formations show a strong dominance of light rare earth elements, especially in the FM.P.Balang pits. Heavy rare earth elements aren't as common, and you mostly find them in the FM.P.Balang PIT GTR-2. This probably indicates some geochemical variations either during the initial burial or changes that occurred after coal formation, which have determined the distribution of these elements. Besides this, elements like Sc and Gd are Really elevated in the Balang mines, which supports the concept that there is genuine geochemical diversity at work here.

The diverse circulation as well as pronounced enrichment of LREEs in certain coal appears might show variants in resource product, paleoenvironmental problems together with diagenetic procedures. These searchings for associate recognized patterns of REE incident in coal, highlighting the stratigraphic and also spatial aspects regulating component movement coupled with build-up in continental sedimentary systems. In recap coal examples from FM.P.Balang display greater focus along with more comprehensive circulations of REEs specifically LREEs than FM.BPN PIT examples showing that each geological setup has unique geochemical features. The enrichment of REEs in the FM. P. Balang Formation can be credited to numerous geological as well as geochemical aspects. Greater mineral issue material specifically clay minerals along with sulfide stages such as pyrite, supplies desirable websites for REE adsorption and also unification. Additionally, depositional settings with better detrital input most likely added to the build-up of REE-bearing minerals in the debris. Diagenetic procedures might have even more helped with the rearrangement and also focus of REEs within certain mineral stages. These incorporated elements describe the dramatically greater REE focus observed in FM.P. Balang contrasted to FM.BPN.

4. Conclusions

Analyses of maceral and mineral phase in-notchcoal ash from the Kutai Basin show strong contrasts between Balikpapan (FM. BPN) and Pulau Balang (FM. P. Balang formations in the region. FM. BPN samples, distinguished by relatively high fixed carbon (45.0–45.2%), low ash ($<2.5\%$) and low sulfur ($<0.15\%$), demonstrate good combustion quality but less REE potential. The FM P. Balang samples are quite different. They have a lot more ash, between 10.8 and 11.2%, and a lot more sulfur, ranging from 3.7 to 6.6%. They also have a high amount of iron oxide, up to 14.2%, which suggests that the minerals in these samples are more complex and maybe even repeated in some way. This complexity seems to be linked to the way some elements, like rare earth elements, transition metals, and ilmenite, are associated with each other, leading to lower values of a specific measure called $Cr_{ef}(REC)$. When we look at the geochemical data, we see that the FM P. Balang samples, especially in the PIT GTR-2 area, have a lot more of certain elements than what is typically found in the upper continental crust. For example, the levels of La, Ce, Nd, and Y are 24.3, 42.2, 51.5, and 33.5 ppm, respectively, which are all higher than the average levels of 30, 34, 26, and 22 ppm for these elements in the crust. The heavy rare earth elements, or HREEs, are generally found in smaller amounts but are still detectable in GTR-2, with Dy and Er at 5.0 and 5.3 ppm. Additionally, Sc is enriched at 28.5 ppm, which is twice the crustal average of 14 ppm. These findings suggest that the FM P. Balang samples have some unique

characteristics that set them apart from other samples, particularly in terms of their mineral composition and elemental enrichment.

These results show that the distribution of REEs is controlled by the processes of depositional and diagenetic origin, suggesting that receptor activity for combustion ash from Pulau Balang coal is greater. In addition to being a combustion by-product, Kutai Basin coal ash may become the main source of critical elements for future sustainable raw materials supply concepts. On economics, the high sustainable concentration of REE has been low from FM. The significant concentrations of these critical elements in the P. Balang Formation suggest that it may be a promising secondary resource for these metals. These concentrations, whilst lower than what is usually found in conventional REE ores, are still similar to those reported for coal-derived material worldwide. This indicates that coal ash from this formation could help diversify REE supply with the appropriate extraction technologies.

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