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Geological Characterization of Rare Earth Elements in Aceh's Igneous Rocks: A Step Toward Sustainable Mining

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ABSTRACT

This study investigates and characterizes the presence of rare earth elements (REEs) in igneous rock samples from the Lokop geological complex in East Aceh, Indonesia. The Lokop geological area is strategically significant due to its underexplored potential for REE resources, since Indonesia aims to enhance its contribution to the global low-carbon transition through sustainable mineral development. Twenty rock and soil samples were analyzed using X-ray diffraction (XRD) and scanning electron microscopy (SEM-EDS) for mineralogical and petrographic characterization, revealing albite-rich plagioclase feldspars hosted in quartzite. REE trace analysis via inductively coupled plasma optical emission spectrometry (ICP-OES) showed Total Rare Earth Elements and Yttrium (TREE+Y) concentrations ranging from 111.20 to 1727.30 ppm. The content of Light Rare Earth Elements (LREEs), ranging from 75.30 to 1225.40 ppm, was significantly higher than that of Heavy Rare Earth Elements (HREEs), which ranged from 35.90 to 501.90 ppm. The highest TREE+Y concentration (1727.30 ppm) was observed in an andesitic rock sample from the Kolon riverbank outcrop, predominantly composed of LREEs, including Cerium (944.90 ppm) and Neodymium (195.50 ppm). The LREE concentration, primarily Lanthanum (498.70 ppm), was also present in this sample. This research provides an important foundation for the sustainable development of Indonesian REE resources, contributing to the global low-carbon economy.

1. INTRODUCTION

The shift toward clean energy is a crucial strategy for achieving low-carbon development. The transportation sector is identified as the second-largest contributor to global energy-related emissions, accounting for 25% of total energy-related carbon emissions worldwide [1]. Consequently, future research and development in critical mineral resources will play a pivotal role in this transition. Rare Earth Elements (REEs) are among the essential materials required for manufacturing low-carbon technologies, including nickel metal hydride (NiMH) batteries, as well as other technologies like solar power, wind energy, and geothermal systems. As the demand for clean energy grows, so does the need for REEs, which are indispensable for developing technologies such as wind turbines, solar panels, and electric vehicle batteries.

The success of this transition is strategically vital for meeting the goals of the Paris Agreement, even if it necessitates an increase in mineral mining to support a large-scale shift to clean energy. In 2017, the World Bank released a report titled "The Growing Role of Minerals and Metals for a Low-Carbon Future", emphasizing that a low-carbon future will be unattainable without expanding the mining activities needed for essential minerals [2]. To address this need, the World Bank introduced the Climate-Smart Mining Initiative as a guideline to promote responsible mining practices for minerals essential to the clean energy transition, aiming to protect the environment in the process.

The current global focus is on expanding the use of solar panels, wind turbines, geothermal energy, and vehicle batteries. Consequently, as shown in Figure 1, the rising demand for rare earth materials essential to producing these technologies is inevitable. This shift will impact mining activities for critical materials, including Rare Earth Elements

(REEs), as clean technologies require more minerals than fossil fuel technologies. In photovoltaic production, critical materials like molybdenum and cadmium are essential for manufacturing thin-film solar cells [3]. Furthermore, among the 15 lanthanide elements, also known as rare earth elements, neodymium and dysprosium are currently used in direct-drive wind turbines, which employ generators with permanent magnets made from rare earth minerals. In silicon-based solar cell production, trivalent REE ions like Pr^{3+}, Gd^{3+}, Eu^{3+}, and Er^{3+} are utilized as nanoparticle-based materials to enhance the conversion efficiency of these solar cells. In addition, other rare earth materials, such as cerium, lanthanum, neodymium, and praseodymium, have been extensively used to enhance the efficiency of NiMH batteries in hybrid electric vehicles [2]. However, the global REE market faces challenges such as geopolitical tensions, environmental concerns, and supply chain disruptions, given that over 70% of REEs are produced in China. These issues highlight the urgency of diversifying REE sources and promoting sustainable mining practices.

REEs, or Rare Earth Elements, are not truly rare as they are present in common minerals, though typically in very low concentrations. These elements include fifteen lanthanides: Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), and Lutetium (Lu), as well as Scandium (Sc) and Yttrium (Y) [4, 5]. The average abundance of these elements in the Earth's crust varies, with Cerium (Ce) at 66 ppm, Neodymium (Nd) at 40 ppm, Lanthanum (La) at 35 ppm, and Thulium (Tm) at just 0.5 ppm [6]. China is currently the leading global producer of Rare Earth Oxide (REO) [7, 8]. It is estimated that over 70% of rare earth minerals currently produced in China [3].

Weng et al. [9] reported that the REE market peaked in 2006, with 133,000 tons or approximately 97.1% of rare earth oxides (REO) supplied by China [9, 10]. Figure 1 illustrates the global production of rare earth oxides (REO) from 2012 to 2023, categorized by major producing countries: the United States, China, Australia, and other nations [11]. Over this period, there is a noticeable upward trend, particularly from 2018 onward, indicating a significant rise in REO mining activities worldwide. China consistently dominates production, reflecting its status as the largest supplier of rare earth elements, crucial for various advanced technologies. Australia and the United States also show gradual increases, likely due to growing demand for rare earths in clean energy, electronics, and defense industries. By 2023, global production approached 400,000 tons, highlighting intensified mining efforts driven by the need for sustainable technology materials. This trend underscores the critical role of REEs in transitioning to a low-carbon economy, though it also suggests rising environmental and geopolitical implications associated with REE mining. Demand for rare earth elements is projected to increase by three to seven times by 2040 [3].

Despite the increasing global demand over the past three decades and the expectation that this trend will persist, Indonesia's rare earth element resources remain relatively underexplored. Recognizing the strategic importance of rare earth elements in global geopolitics, the Indonesian government has expressed interest in further investigating the feasibility of extracting these elements, particularly those associated with igneous rocks. However, due to the geological challenges involved in identifying these elements at the Earth's surface, research on their exploration in Indonesia is still limited and has yet to be comprehensively studied and documented [5, 9]. Although in the worldwide context, lately the research relating this topic is emerged significantly.

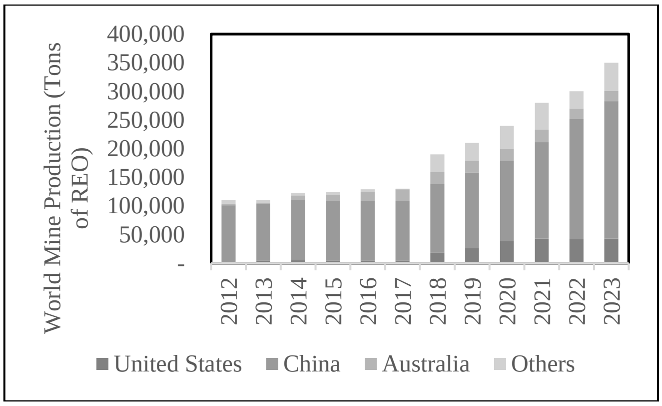


Figure 1. Global rare earth oxide (REO) mine production by country (2012–2023) [11]

Investigating REEs is relatively complex because their occurrence in the Earth's crust differs from that of native metals like gold, copper, and silver. Unlike these metals, REEs are considered non-native due to their reactivity, characterized by large atomic radii and high charge. As a result, REEs are typically found in various host minerals as minor elements [12, 13]. Although REEs can be found in various common minerals on Earth, such as silicates, carbonates, oxides, and phosphates, REE-bearing minerals are only present in specific geological environments [14]. Geological environments that may contain REEs can be categorized into magmatic settings, which can host deposit types like carbonatites, peralkaline rocks, and pegmatites, and sedimentary settings, which facilitate the formation of placer and phosphorite deposits [12].

REEs are generally more readily found in the Earth's crust than in its mantle [15]. They naturally formed in nature but not as native metal themselves [4]. However, as the REEs are difficult to be extracted from their host minerals or rocks due to their low concentrations, therefore only REEs borne in few bearing minerals are considered economic such as in bastnaesite, monazite and xenotime [9]. Therefore, this study attempts to contribute to the gap, particularly in the Indonesian context to investigate and characterize the presence of rare earth elements in the igneous rock. This study is expected to set up the basis for further study on the down-streaming of the REE resources that will be the key to support global low carbon future.

Indonesia's rare earth element resources, including those found in the Lokop geological area in East Aceh, remain underexplored despite their critical potential to diversify the global REE supply. As demand for REEs continues to increase, driven by advancements in clean energy technologies such as wind turbines, electric vehicles, and solar panels, unlocking Indonesia's untapped resources has become increasingly vital. The Lokop geological area is particularly promising due to its complex tectonic and magmatic history, which has likely facilitated the formation of REE-bearing minerals within igneous rocks and associated lithological formations. These minerals, essential for producing components like permanent magnets, advanced batteries, and other low-carbon technologies, position Lokop as a potentially strategic resource hub. Moreover, studying this area offers an opportunity for Indonesia to reduce global reliance on dominant REE producers such as China while establishing its own footprint in the global REE market. By focusing on Lokop's geological complexity and potential resource yield, this research aligns with Indonesia's goals to strengthen its contribution to the global clean energy transition, leveraging sustainable mining practices to ensure long-term environmental and economic benefits.

This study aims to systematically reveal the mineralization characteristics of REEs in the Lokop geological area through detailed rock sample analysis using advanced techniques such as XRD, SEM-EDS, and ICP-OES. The research seeks to determine the mineralogical, geochemical, and petrographic properties of REE-bearing rocks, providing critical data to support future exploration and resource development. Additionally, this study holds broader implications for Indonesia's resource strategy by addressing the knowledge gap surrounding REE occurrences in the region, enabling better-informed policy-making and sustainable development planning. The insights derived from this research will not only serve as a foundation for expanding Indonesia's role in the global REE supply chain but also contribute to the stability of critical material supplies essential for low-carbon technologies. By prioritizing sustainability, this study underscores the importance of integrating environmental and social governance principles into resource development processes, ensuring that mining activities in Lokop contribute positively to both local and global efforts toward a low-carbon future.

2. METHODOLOGY

2.1 Geology of study area and sample distributions

The investigation was conducted administratively within the Serbajadi Subdistrict of Eastern Aceh District, located at coordinates 97° 21’ 20” – 97° 34’ 30” E and 04° 15’ 30” – 04° 21’ 20” N. Sampling was focused around the Kolon and Keloak rivers, which lie near the Kutacane-Pining-Lokop fault, a segment of the Sumatran fault system. Regionally, this area is heavily influenced by tectonic activity and is classified as a highly complex geological site. This tectonic complexity has led to the formation of the Kutacane-Pining-Lokop fault and various fold structures. This fault is part of the Great Sumatran Fault (Semangko Fault) in the eastern region, which remains active today with a northwest-southeast alignment [16, 17]. Anticline and syncline folds are present in nearly every rock formation in the area, especially within Tertiary sedimentary rocks [18].

The Lokop geological area is unique in its REE mineralization potential due to the tectonic and magmatic processes that have occurred over millions of years. The intrusion of granite from the Middle Miocene period into older formations, including the Kluet and Tampur formations, has resulted in the alteration of primary minerals and the formation of REE-bearing minerals. This area’s complex geological history, including active faulting and volcanic activity, contributes to the presence of mineralized zones rich in rare earth elements, making it a promising site for further exploration. The presence of hydrothermal alteration zones and significant weathering processes adds to the mineralization potential, as these processes can concentrate REEs in specific rock types such as granites and andesites, which are abundant in the study area.

Based on the geological map sheet Langsa Scale 1: 250.000 regional stratigraphy of the oldest rock investigation area including the Kluet Formation (Puk) of Permo-carboniferous age [18, 19]. As shown in Figure 2, the oldest bedrock in the study area is the Kluet Formation (Puk), dating to the Permo-Carboniferous period. These rocks consist of dark gray slate with a slightly sandy texture and are prominently exposed along the main river and the Lokop-Pining roadway. Overlying the Kluet Formation unconformably is the Tampur limestone (Totl), which consists of reef limestone and dolomite from the Early Oligocene. Above the Tampur Formation lies the Semeten Volcanic Formation (Tlvm), characterized by Semeten Volcanic andesite, ranging from the Early Oligocene to Early Miocene. This formation is visible in the Kolon trench, identifiable by its dark gray color, thin veins of altered quartz, and the presence of chlorite minerals indicating a propylitic alteration zone. Pyrite mineralization, along with thin veins of pyrite, is also observed within this formation.

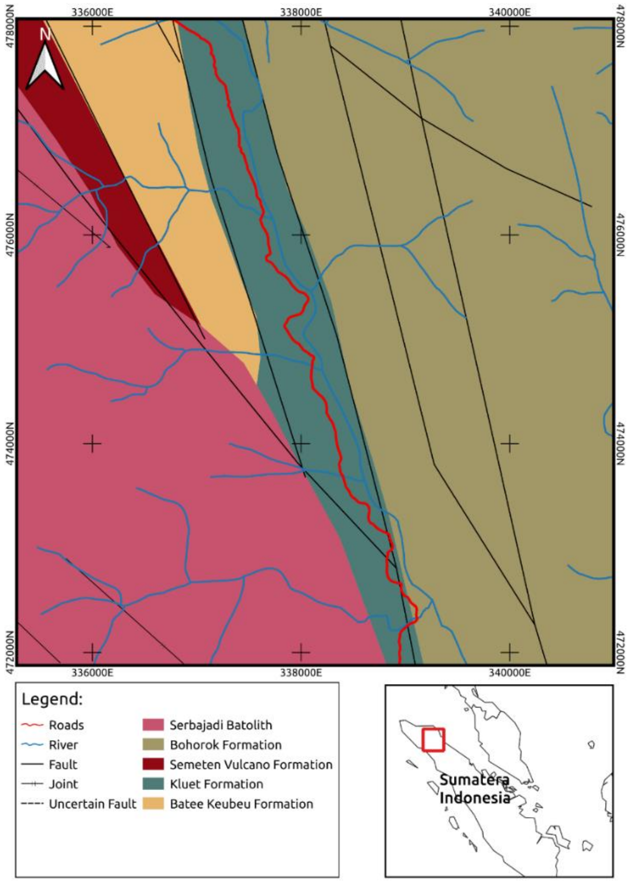


Figure 2. Geological map of investigation sites

Physiographically, the research area and its surroundings are the part of the Blangkejeren-Pining-Lokop valley, which is traversed by the Kutacane-Pining-Lokop Fault in a northwest-southeast direction, which is the eastern part of the Bukit Barisan Mountains [19]. The morphology of the research area is almost entirely in the form of high undulating hills with elevations ranging from 400-1300 m of MSL with steep slopes, which are between 40°-70°. The vegetation cover is dense thicket forest, including protected forest with some areas have been cleared by local residents for plantations.

Two major rivers flow through the study area: Dangla Creek, which flows northward, and Kala Serdang Creek, which flows southward. These rivers follow a sub-parallel pattern influenced by the Kutacane-Pining-Lokop structure. Tributaries, including Kolon and Sepung creeks, exhibit mostly dendritic patterns with localized angular sections due to structural influences. Stratigraphically, the area is covered by rock formations ranging from older to more recent layers.

Additionally, the Kluet Formation (Puk), Tampur Formation (Totl), and Semeten Volcano Formation (Tlvm) were intruded by Lokop granite dating back to the Middle Miocene. This granite unit is visible along the Lokop-Pining Road and upstream of the Kala Serdang Creek. It has undergone significant weathering, resulting in thick residual soil. In some sections of the weathered granite, feldspar minerals have altered into kaolinite. Fresh granite boulders were found along the main river and its branches in the study area, although no granite outcrops were observed.

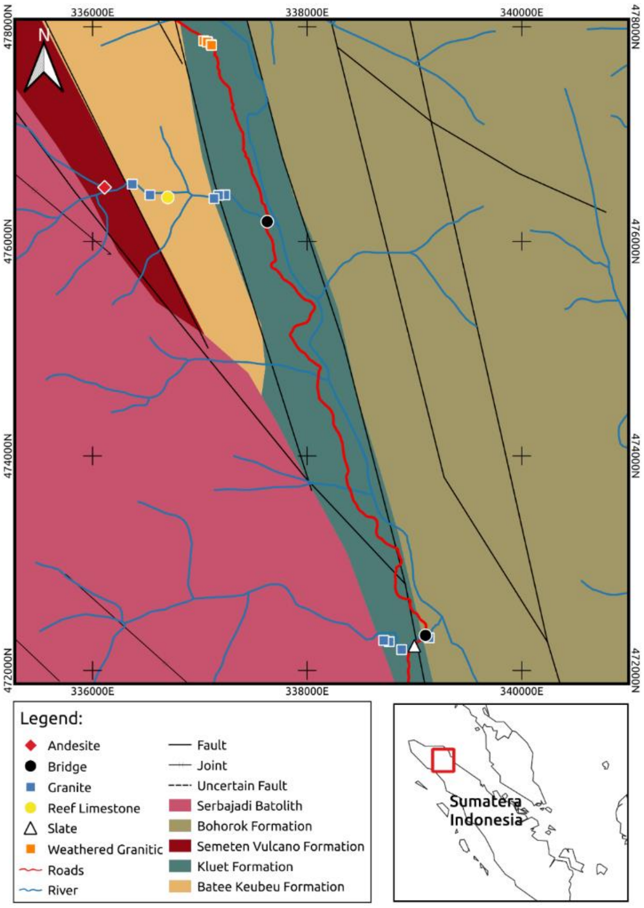


Figure 3. Distribution of collected samples

In igneous rocks, REEs were associated in REE-bearing minerals such as allanite, apatite, titanite, xenotime and monazite during their magmatic evolution in the lower mantle of earth [20]. The understanding of REEs geochemical behaviors in different geological environments such as in limestone, granite, or carbonatite is essential in identifying the transformation process of REE in the weathered rocks [21]. REE mineralization is commonly found across various lithologies in Indonesia, including granite, metamorphic, ultramafic, and alluvial formations. These rock types are present in magmatic belt areas, such as along the Sumatran Fault. REEs are often associated with granitic rocks that have high concentrations of tin (Sn). Additionally, REEs may occur in ultramafic environments, where they are closely linked to nickel and cobalt (Ni-Co) mineralization. The distribution of collected samples then is plotted in the map as shown in Figure 3.

2.2 Sampling method

Samples of REEs associated with fresh granitic rocks were collected by using chip sampling method. This technique involves taking fragments of mineralized rock by using rock hammers, which are then stored in sample bags marked with unique sample identities. Chip sampling was conducted at various depths of 0.5–1 meter, with samples collected every 10 meters along the riverbanks and at outcrop locations. A total of 12 chip samples were collected from areas showing visible mineralization. Chip sampling was also used to collect samples of mineralized rocks such as andesite and reef limestone found in outcrops. Soil samples were also collected from some weathered profiles by using channel sampling, which involves making a channel along the profile showing mineralization traces, with a width of 5 to 10 cm and a depth of 3 to 5 cm to collect soil samples. Channel sampling was carried out at depths ranging from 0.5 meters to 2 meters, and a total of 8 samples were taken from different sections of the weathered profiles.

2.3 Samples analysis

All samples preparation and analysis of this study were conducted at the Indonesian National Research and Innovation Agency (BRIN) laboratories. The petrographic analysis of the collected samples is examined by using Scanning Electron Microscope - Energy Dispersive Spectroscopy (SEM-EDS). The scanning electron microscope (SEM) is equipped with a focused beam of high-energy electrons to generate a variety of signals at the surface of solid samples. The signals that obtain from electron-sample interaction enables SEM analysis to provide compositional information of samples such as external morphology (texture), chemical composition, and crystalline structure and orientation of samples imaged mineral grains in samples surface quantitatively and qualitatively.

A robust understanding of mineral alteration is crucial in analyzing rare earth depositions. Therefore, we used X-Ray Diffraction (XRD) analysis to characterize the minerals in the weathered rocks. X-Ray Diffraction (XRD) is a non-destructive, rapid analysis technique primarily used for phase identification of crystalline materials. It works by observing the diffraction pattern produced when a light beam, directed at a sample, is refracted by the material's crystal lattice, revealing the specific atomic structure. This method allows for both qualitative and quantitative identification of various crystal forms of the compounds. Additionally, XRD can identify fine-grained minerals such as clay, which may be important in the context of mineral alteration. The identification is performed by comparing the X-ray diffraction pattern obtained with known reference patterns. For optimal analysis, the sample size should be finely ground to about 200 mesh. The XRD analysis in this study was conducted using a PANalytical EMPYREAN diffractometer, with a scan range of 5°–70° 2θ, a step size of 0.02°, and a scan step time of 25 seconds to ensure high-resolution diffraction patterns.

Finally, the element tracing of REE is analyzed by using Inductively coupled plasma optical emission spectrometry (ICP-OES). Rare earth elements that can be analyzed by using ICP-OES include Ce, Dy, Eu, Er, Ho, Gd, La, Lu, Nb, Nd, Pr, Sm, Tb, Tm, Y, Yb, and Sc. The measurement of REEs requires a high enough energy to the electron excitation, which is possible by using Inductively Coupled Plasma (ICP). Inductively coupled plasma optical emission spectrometry (ICP-OES) is a method based on ion-excitation and generate a beam. ICP-OES has several advantages compared to other methods as it can identify and measure all measured elements simultaneously in time relatively short time and a high degree of accuracy.

However, element analysis by using ICP-OES requires decomposition of solid samples. The objective of decomposition is to dissolve solid samples to be solution which contains the metals. Crystal structure of minerals and their chemical compositions will be decomposed during decomposition process. Decomposition method can be done by using acid mixtures of HF, HNO_3 and $HClO_4$ with respective concentration ratio of 7:3:1 [22].

The research methodology involves several key procedures aimed at synthesizing lithium titanium oxide (Li_2TiO_3) adsorbent and assessing its efficacy in lithium recovery from geothermal brine. Initially, the Li_2TiO_3 adsorbent is synthesized through a solid-state reaction utilizing TiO_2 (anatase type, Merck, $\geq$ 99%) and Li_2CO_3 (Merck, $\geq$ 99%). Various mol ratios of Li to Ti are mixed at room temperature for 30 minutes before being placed into a crucible and calcined in a muffle furnace. The calcination temperature is varied (550°C, 700°C, and 850°C) over 4 hours with a heating rate of 5, 7, and 9°C/minute. Following calcination, the adsorbent is ground using a mortar and sieved. Samples of the adsorbent are then subjected to X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) analyses to characterize its structural and morphological properties.

In the desorption process, the synthesized Li_2TiO_3 adsorbent is treated with acid to release lithium ions (Li^+) and replace them with hydrogen ions (H^+) via ion exchange. This desorption occurs when stirring at 350 rpm for 24 hours at 40°C using hydrochloric acid at pH 1. The liquid samples are periodically analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES), and the solid adsorbent is separated from the hydrochloric acid solution using a vacuum pump filter. The solid adsorbent is then analyzed using SEM, XRD, and XRF to observe any changes in structure and composition.

3. RESULT AND DISCUSSION

3.1 Mineralogy analysis

The identification of the weathering profiles was conducted by evaluating the color, structure and texture of soil clay-mineral formations. The weathered profiles usually exhibit an enrichment in clay minerals, and are characterized by a dark brown color, high degree of oxidation, and poor compaction [23]. To investigate mineralogical alterations caused by the weathering process in igneous rocks within the Lokop geological complex, we conducted XRD analysis on soil samples collected from weathered horizons, as shown in Figure 4, with a thickness ranging from 2 to 4 meters.

Horizon A is the uppermost layer of the profiles, with a thickness ranging between 1 to 2 m, and is distinguished by its dark brown coloration and low degree of compaction. Meanwhile, Horizon B is the middle layer of the section and is approximately 0.5 to 1 meter thick, appears brown in color, and mainly consists of soft clay minerals. The lowest part of the section, horizon C, is the weathering front layer, white in color and has a thickness of 0.5 to 1 meter. This alteration is indicative of the transformation of feldspar minerals into Albite in horizon C, and the further alteration of clay minerals in horizon B into Gibbsite ($Al(OH)_3$), which plays a critical role in modifying the geochemical behavior of REEs by interacting with them through adsorption and precipitation processes. This transformation impacts the mobility and solubility of REE species in the soil, influencing their concentration and distribution across the horizons. This effect is further exacerbated by the hydrothermal alteration of feldspars and other minerals in the rock, leading to the enrichment of LREEs in specific layers.

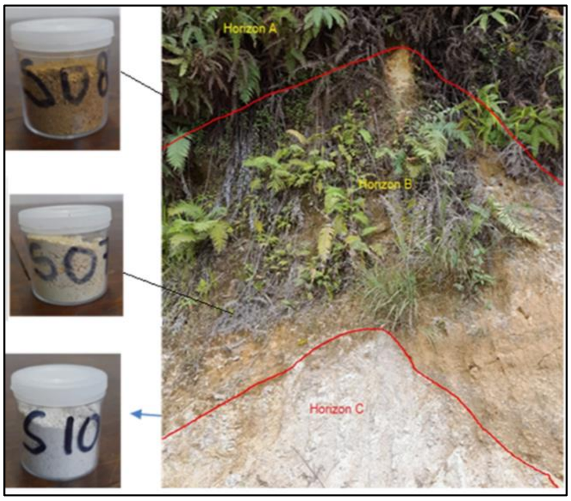
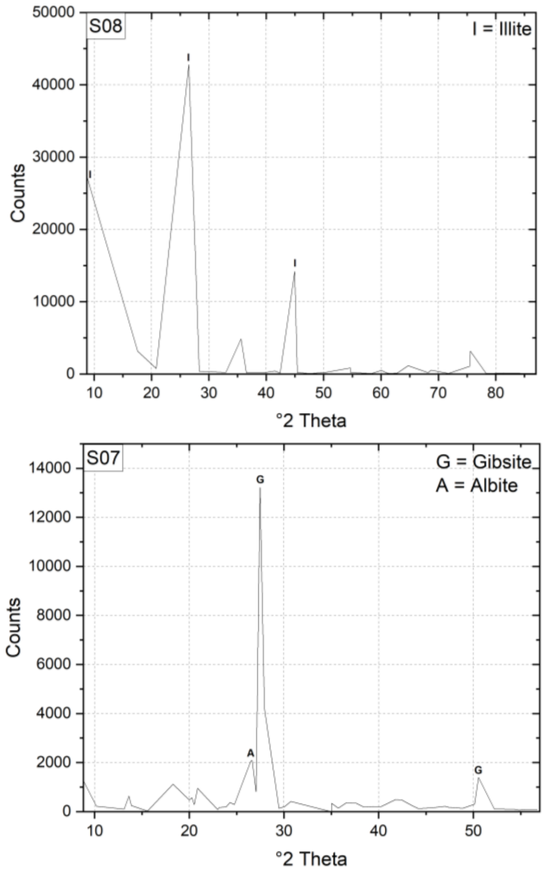


Figure 4. Weathering profile of granitic rock consisting of Horizon A, B and C



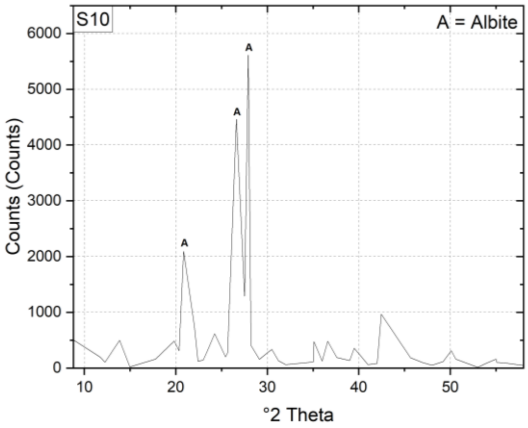


Figure 5. XRD result of horizon A (S08), horizon B (S07) and horizon C (S10), which shows the albitization of bedrock where feldspar is transformed into Albite before altered further into Gibbsite

The formation of Gibbsite significantly alters the geochemical dynamics of the environment, affecting the distribution of REEs. Gibbsite, as an alumina-rich mineral, can bind to certain REEs such as cerium (Ce) and lanthanum (La), leading to the concentration of these LREEs in the weathered layers. Gibbsite's ability to absorb and precipitate REEs plays a key role in the geochemical partitioning of these elements, as its formation creates localized zones of high REE concentration, which may enhance the economic potential of these deposits. This process is crucial in understanding how the weathering of parent rocks can significantly alter the concentration and speciation of REEs in weathered profiles, particularly in the context of hydrothermal alteration.

The XRD analysis of the soil samples (Figure 5) collected from horizon profile found that horizon C is dominated by Albite ($NaAlSi_3O_8$) which is a plagioclase feldspar mineral. Differently, the XRD analysis also indicate that horizon B is largely composed of Gibbsite ($Al(OH)_3$). Finally, in horizon A which is the uppermost layer, illite was found as the result of hydrothermal alteration of micas and feldspars. The alteration process of the horizon layer will be discussed in the discussion section.

3.2 Petrography analysis

SEM analysis is extensively used to examine mineral morphology, including the size, texture, and shape of minerals. In this study, Scanning Electron Microscope (SEM) - Energy Dispersive Spectroscopy (EDS) analysis was conducted using a JEOL JSM-6510LA at the Laboratory of Advanced Nuclear Materials, National Research and Innovation Agency (BRIN). Three samples, S14, S19, and S20, were selected for SEM-EDS analysis. The results from all tested samples revealed a correlation between the mineralogical analysis of weathered rock profiles and petrographic analysis of fresh rock samples, confirming that these samples are igneous and alkaline in nature.

Figures 6 and 7 present the andesite rock sample and the results of Scanning Electron Microscope (SEM) - Energy Dispersive Spectroscopy (EDS) analysis for Sample S19. This rock, collected from an outcrop along the Kolon riverbanks, indicates mineralization, as evidenced by the presence of disseminated pyrite. The SEM analysis in Figure 7 reveals a relatively uniform texture with compact structures within the andesitic rock sample.

Figure 6. The andesite rock sample (S19) collected from the outcrop in the Kolon riverbank

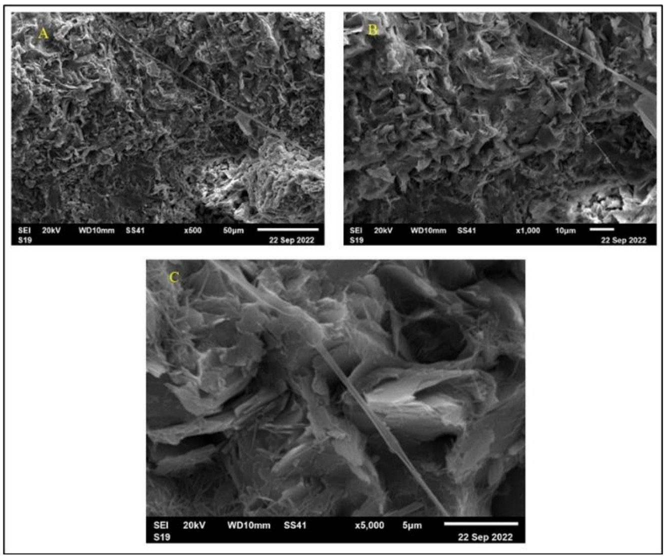


Figure 7. Scanning electron photomicrographs of andesitic rock sample (S19) scanned with 500x magnification (A), 1000x magnification (B) and 5000x magnification (C)

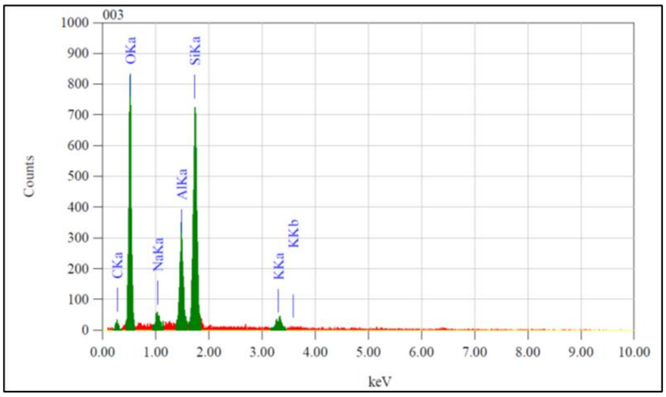


Figure 8. EDS spectra of sample S19

Additionally, the EDS spectra in Figure 8 shows that silicon (Si) and aluminum (Al) are the primary elements in Sample S19, with mass percentages of 31.72% and 11.12%, respectively. Other elements detected include sodium (Na) and potassium (K), with concentrations of 2.30% and 3.10%, respectively. The presence of Si and Al indicates a significant composition of quartz (SiO_2) and alumina (Al_2O_3) in the rock. Furthermore, the presence of Na and K suggests primary enrichment in Na_2O and K_2O, indicating that the granite is classified as an alkaline rock [24].

Figure 9 displays a granitic rock sample, labeled S20, which was collected from the Kolon River. It is anticipated that the parent rock of this sample lies further upstream along the river. The SEM analysis, shown in Figure 10, reveals that the sample possesses equigranular structures, characterized by uniformly sized mineral grains, and compact textures, indicative of strong interlocking among mineral crystals. The rock exhibits a gray coloration and is visibly enriched with various minerals, including biotite, quartz, plagioclase feldspar, and potassium feldspar, suggesting a mineralized composition. The presence of these minerals not only reflects the sample's granitic nature but also hints at the geological processes that may have contributed to its formation and mineral content. These mineral components, especially feldspar varieties, play a significant role in identifying the rock's alkaline properties and support the classification of this sample as an igneous formation with potential for rare earth element enrichment.

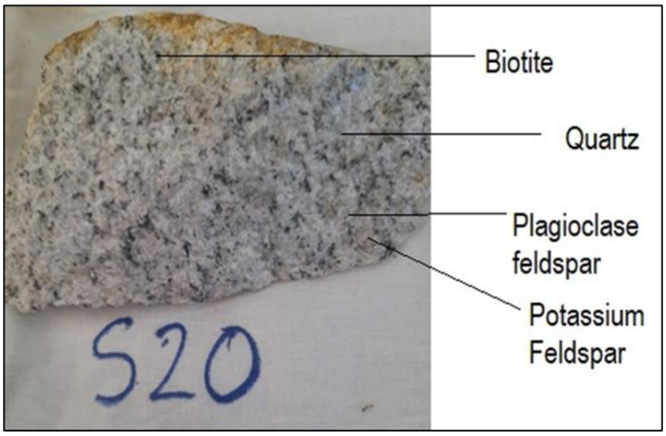


Figure 9. The granitic rock sample (S20) collected in the Kolon Riverbank indicating the presence of mineralization of biotite, quartz, plagioclase feldspar and potassium feldspar

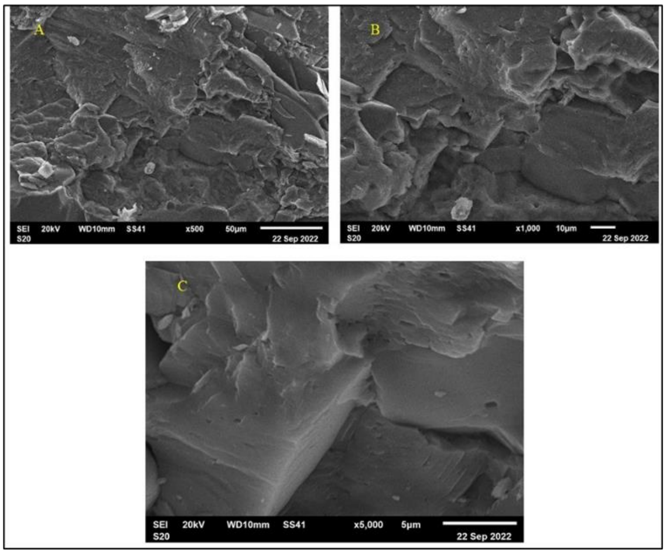


Figure 10. Scanning electron photomicrographs of granitic rock sample (S20), scanned with 500x magnification (A), 1000x magnification (B) and 5000x magnification (C)

Furthermore, as depicted in Figure 11, the EDS spectrum analysis highlights silicon (Si) as the predominant element in the S19 rock sample, suggesting that it forms a major component of the sample's mineral structure. Quantitatively, the mass composition consists of 29.65% silicon, 6.10% aluminum (Al), and 1.95% sodium (Na). The notable absence of potassium (K) in this sample provides additional insight into the mineral classification, suggesting that the rock's primary mineral could be plagioclase feldspar, a common silicate mineral in igneous rocks. Plagioclase feldspar is a significant indicator of igneous processes and is known to lack potassium, distinguishing it from potassium feldspar varieties. This mineral composition further suggests that the rock has undergone specific geologic conditions, particularly related to the cooling and solidification of magma, which favored the formation of sodium-rich, potassium-poor feldspar. The prevalence of plagioclase feldspar in this sample may also imply alkaline properties within the geological environment where this sample was formed, contributing valuable data to the mineralogical characterization of the Lokop geological complex.

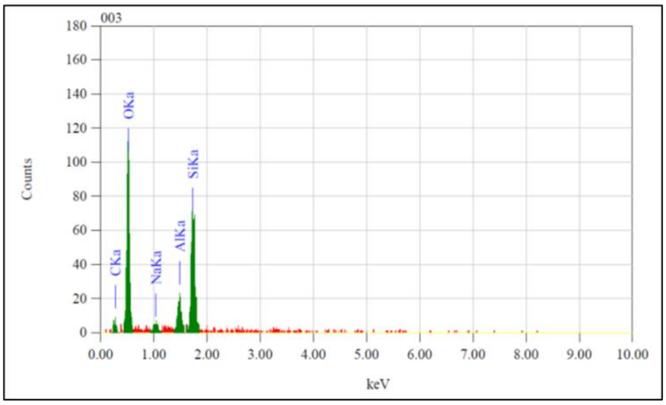


Figure 11. EDS spectra of sample S20

Figure 12. The granitic rock sample (S14) collected in the Kolon river

Figure 12 presents a granitic rock sample collected from the Kolon River, showcasing its geological characteristics typical of igneous formations in the area. The SEM analysis, illustrated in Figure 13, reveals that this granitic sample possesses equigranular structures, where mineral grains exhibit a uniform size distribution, indicating a consistent cooling rate during the rock's formation. The compact textures observed suggest strong mineral interlocking, which points to a durable crystalline structure within the sample. This equigranular structure, often found in slowly cooled intrusive rocks like granite, allows for a stable mineral arrangement and provides insights into the rock's formation history and the environmental conditions present during crystallization. The compact texture also indicates minimal porosity, further suggesting that the mineral grains have undergone limited alteration and remain in close contact, which is often associated with high stability and resilience of the rock matrix. This structural information aids in understanding the geological history of the Kolon River area, contributing valuable context to the mineralogical composition of the Lokop geological complex.

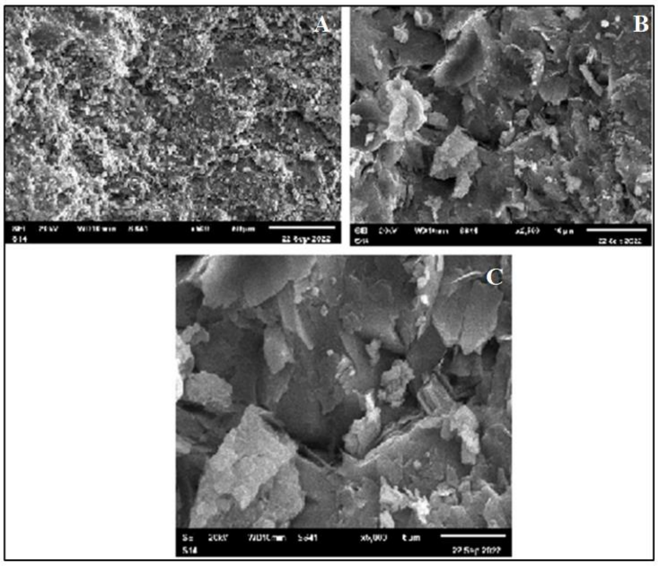


Figure 13. Scanning electron photomicrographs of granitic rock sample (S14) collected on from the Kolon creek, scanned with 500x magnification (A), 1000x magnification (B) and 5000x magnification (C)

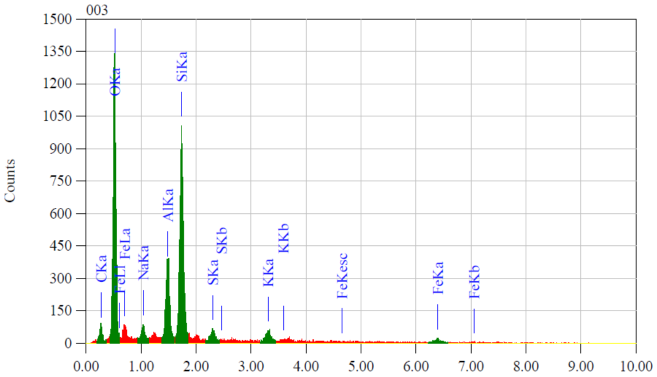


Figure 14. EDS spectra of sample S14

The EDS spectrum analysis for sample S14, shown in Figure 14, reveals that the rock is composed primarily of silicon (Si), aluminum (Al), potassium (K), and sodium (Na), with mass percentages of 24.52%, 8.31%, 3.26%, and 1.63%, respectively. Unlike other samples analyzed, S14 also shows significant amounts of iron (Fe) and sulfur (S), with mass percentages of 9.13% and 1.89%, respectively. The presence of iron and sulfur suggests possible mineralization processes or the formation of sulfide minerals within this rock. The distinctive red coloration observed in the sample indicates that iron oxidation has taken place, altering the rock's natural color. This oxidation process, common in environments with exposure to air or water, can contribute to weathering effects and may affect the rock's stability and mineral composition over time. The combination of elements found in sample S14 adds valuable insight into the geochemical environment of the Lokop geological complex, suggesting localized variation in mineralization and oxidation processes within the area.

3.3 REE trace element analysis

REE trace element analysis was performed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Fresh granite solid samples were first digested into a solution before analysis. Out of the 12 collected fresh rock samples, 8 were selected for ICP-OES examination. The total REE + Y content in the rock samples ranged from 111.20 to 403.50 ppm, primarily consisting of Light Rare Earth Elements (LREEs) at concentrations between 75.30 and 1225.40 ppm. The samples also contained Heavy Rare Earth Elements (HREEs), though in much lower concentrations, ranging from 35.90 to 501.90 ppm. Analysis of the andesite sample (S19) reveals that it contains the highest TREE+Y concentration among all samples, measuring 1727.30 ppm. This includes a substantial proportion of Light Rare Earth Elements (LREEs) at 1225.40 ppm. Cerium (Ce) and Neodymium (Nd) are the most abundant elements within the sample, with concentrations of 944.90 ppm and 195.50 ppm, respectively. Additionally, the sample contains Heavy Rare Earth Elements (HREEs) at 501.90 ppm, primarily dominated by Lanthanum (La) with a concentration of 498.70 ppm.

The LREE/HREE ratio in the Lokop samples, particularly the high proportion of LREEs in sample S19 (LREE/HREE ratio: 2.44), indicates a strong potential for LREE mineralization. This ratio is often considered a diagnostic factor for assessing the economic feasibility of REE deposits, as LREEs are commonly found in higher concentrations and are more commercially viable compared to HREEs. Moreover, a high LREE/HREE ratio reflects specific geological processes, such as fractional crystallization during magmatic differentiation or selective mobilization during hydrothermal alteration. These processes favor the enrichment of LREEs in felsic igneous rocks and are often observed in alkaline geological environments like Lokop. Furthermore, tectonic activities, such as those along the Kutacane-Pining-Lokop Fault, may enhance REE concentration by facilitating hydrothermal fluid flow and creating ideal conditions for LREE enrichment. Globally, regions with high LREE dominance are recognized for their economic potential, suggesting that the Lokop area warrants further exploration to assess its viability as a significant source of LREEs.

REEs are primarily deposited in association with carbonate, igneous, and metamorphic rocks [25, 26]. Alkaline igneous rocks are commonly found in Indonesia, including within the Lokop geological complex. The granitic rocks in this area range from moderately to heavily weathered. Mineralogical analysis of host rock samples, conducted through SEM-EDS, identified sodium (Na) and potassium (K), indicating a felsic volcanic geological environment. In these host rocks, hydrothermal alteration processes involve the replacement of primary igneous minerals, such as plagioclase, orthoclase, quartz, biotite, muscovite, amphibole, pyroxene, and titanomagnetite, with more stable alteration minerals [27].

XRD analysis of the samples reveals significant decomposition of the rock-forming minerals, except for quartz. The granitic rocks in the Lokop geological complex show moderate to heavy weathering. Analysis of soil samples through XRD indicates that the host rock has undergone albitization, evident from the dominant presence of albite in the bedrock layer (horizon C) of the weathering profiles. This transformation results from feldspar alteration and its subsequent replacement by albite. Analysis of fresh andesitic rock samples also shows that these rocks are rich in potassium (K) and sodium (Na), supporting their classification as felsic volcanic rocks. In such K- and Na-rich rocks, alterations affect the texture, mineralogy, and chemical composition, often involving the development of silicate clay minerals such as kaolinite, illite, and montmorillonite [28].

In a specific section of the weathered crusts in Lokop, the weathering profile can be divided into three distinct horizons: horizon A, which represents a lateritic profile, and horizons B and C, which correspond to the weathered horizon and the weathering front, respectively. Analysis of sample S10, collected from horizon C, reveals albitization of igneous andesitic rock. Through this process, portions of alkali feldspar within the rock (refer to Figure 10) have been altered and replaced by albite. Additionally, in the alkaline environment of felsic volcanic rocks, the clay minerals in horizon C undergo further alteration, transforming from kaolinite into gibbsite [29]. In the alkaline environment of felsic volcanic rocks, clay minerals undergo further alteration, leading to changes in composition from kaolinite to gibbsite, as observed in the upper saprolite layer (horizon B). The formation of gibbsite in horizon B results from the incongruent dissolution of kaolinite in horizon C during the initial stages of the weathering process. This process involves the hydrolysis reaction, where feldspars break down into soluble forms of aluminum (Al) in solution, which then crystallizes as gibbsite [30]. The presence of illite in horizon A indicates the decomposition of certain micas and feldspars, likely resulting from hydrothermal alteration processes.

Furthermore, SEM-EDS analysis reveals that the rock samples from the Lokop complex are rich in sodium (Na) and potassium (K) feldspar minerals. In these rocks, the mineral composition typically includes 20–40% quartz, 50–80% K-feldspar, Na-plagioclase, and micas, primarily biotite with occasional muscovite. For instance, SEM analysis of an andesite sample (S19), with a high ΣREY (total rare-earth elements and yttrium) concentration of 1727.30 ppm, shows the sample contains 29.65% silicon (Si), 6.10% aluminum (Al), and 1.95% sodium (Na). Other samples, with lower ΣREY concentrations ranging from 111.20 to 403.50 ppm, also contain more than 20% quartz and detectable levels of Al in each sample. The presence of Al, as confirmed by SEM-EDS and XRF tests, suggests that accessory minerals within Lokop's igneous rocks may include albite-rich feldspars within a quartzite host. The process of albitization, in which alkali and plagioclase feldspars are replaced by albite, is observed in various rock types and tectonic settings and is a common occurrence during the hydrothermal alteration of granitic formations [31]. Albitization is frequently linked to mineral and ore deposits, where alkali and/or plagioclase feldspar minerals are altered into nearly pure albite ($Na(AlSi_3O_8)$).

In most geological environments the REEs are considered immobile, however there is abundant evidence in alkaline felsic igneous rocks REEs can be mobilized either by hydrothermal or by the combination of magmatic and hydrothermal alterations [24, 32]. The alkali metasomatic process may cause REEs heavily leached form their albitized granites [33]. The alkali metasomatic is usually controlled by tectonic activity [34]. Tectonic activity along the fault zones of the Kutacane-Pining-Lokop Fault, part of the larger Sumatran Fault system, may influence the alkali-metasomatic processes responsible for REE enrichment within the Lokop geological complex.

Comparison with other REE-rich regions, such as the Bayan Obo deposit in China and the Mount Weld deposit in Australia, reveals that the Lokop area has moderate ΣREE+Y concentrations. However, Lokop's geological uniqueness, characterized by its igneous rock-hosted REE deposits and significant tectonic activities, provides a valuable contrast to other deposits. For instance, the Bayan Obo deposit is known for its carbonatite-hosted REEs, while the Mount Weld deposit is associated with lateritic weathering of carbonatite. In comparison, Lokop's potential lies in its magmatic and hydrothermal processes, which have enriched LREEs within felsic igneous rocks. This distinction not only highlights the diversity of global REE sources but also emphasizes the need to explore and understand underexplored regions like Lokop to diversify the global supply chain. The increasing demand for REEs, coupled with supply risks due to the dominance of a few producers, underscores the strategic importance of developing deposits like those in Lokop, particularly for supporting clean energy technologies and reducing reliance on traditional sources.

4. CONCLUSIONS

To investigate the presence of REE-bearing minerals in rock units within the Lokop area of East Aceh, a total of 20 rock samples were collected from sites with varying geological settings. Slate outcrops were abundant along the Keloak and Kolon riverbanks, while reef limestone and andesite outcrops were observed on cliffs around Kolon Creek. Analysis of granitic rock samples from Kolon Creek indicated enrichment in silicon (Si) and aluminum (Al), with mass percentages ranging from 24.52% to 29.65%. Additionally, the andesite sample displayed a higher Si concentration of 31.72%. The presence of Si and Al suggests that quartz (SiO_2) is a major mineral in these rocks, potentially hosting REE-bearing minerals such as monazite, which contains cerium, lanthanum, and neodymium.

Further examination of 8 fresh rock samples using ICP-OES revealed that total rare earth element (TREE+Y) concentrations in the rock samples ranged from 111.20 to 403.50 ppm, predominantly composed of Light Rare Earth Elements (LREEs) with values between 75.30 and 1225.40 ppm. Although Heavy Rare Earth Elements (HREEs) were also present, their concentrations were much lower, ranging from 35.90 to 501.90 ppm. The highest TREE+Y concentration was found in an andesite sample from an outcrop along the Kolon riverbank, reaching 1727.30 ppm, with a large proportion of LREEs at 1225.40 ppm. Cerium (Ce) and Neodymium (Nd) were the most abundant elements, with concentrations of 944.90 ppm and 195.50 ppm, respectively, while HREE content in this sample was 501.90 ppm.

This study provides baseline information for future research on REEs in the Lokop geological complex. However, limitations such as the limited sample size may result in regional underrepresentation of results, affecting the comprehensiveness of the findings. The small number of samples, particularly from highly prospective areas like the andesite outcrop, may not fully capture the variability and extent of REE mineralization within the Lokop area. Additional sampling from more diverse geological contexts is needed to provide a clearer understanding of REE distribution in the region.

Access difficulties and thick soil cover over the outcrop further hindered comprehensive sample collection. Specific future research directions include further drilling to obtain deeper rock profiles, detailed geochemical analyses to understand the processes influencing REE concentration, and advanced geophysical methods such as Induced Polarization (IP) surveys to detect subsurface mineralization. These approaches are essential to better delineate REE-rich zones, assess their economic viability, and support sustainable resource development in the Lokop geological complex.

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