Potential REE-Li resources in lateritic granite in Indonesian granitoid formations: A review

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Abstract. The long-term growth trajectory of numerous industries remains dependent on rare-earth elements and lithium (REE-Li) resources, even if China began restricting the supply of REE. As critical raw minerals, REE-Li resources have become a sensitive issue, with the preservation of reserves framed as concerns over protecting the country's sovereignty. REE-Li bearing minerals are surmised to have originated from granite parent rocks. The granite belt in Indonesia is extensive on the Bangka Belitung Islands, West Kalimantan, and West Sulawesi, areas associated with high levels of radioactivity. This study discusses a conceptual analysis on the presence of REE-Li in granitic rock and lateritic granite based on previous studies both in general and in the given area. The region is mineralized with REE-Li bearing minerals in granite, which are absorbed onto clay minerals from weathered granite.

1. Introduction
The Indonesian government is committed to developing high-tech processing infrastructure and has passed legislation to regulate the mining of radioactive energy (Undang-Undang Cipta Kerja No.11, 2020, Article 9), which stipulates that state-owned enterprises may collaborate with private companies to engage in mining associated-radioactive minerals. Rare-earth elements and lithium (REE-Li) are associated-radioactive minerals crucial for developing the high-tech technologies behind Li-batteries, hybrid cars, and magnet alloys – provided these are supported by the availability of raw materials of REE-Li raw materials.

REE-Li deposits can be found in granitoid rock and its weathering products. During the weathering of granitoid, which is mineralized with REE-Li bearing minerals, the REE-Li ions are absorbed onto clay minerals (e.g., kaolinite, smectite, and illite), enriching specific layers within the soil profile [1]. Typically, radioactive elements (e.g., thorium and uranium) are considered impurities because of the accompanying negative issues and impact on mineral exploration and processing. Thus, for REE-Li mining, it is preferable to choose lateritic granite with low radioactive content, which is also easily leached [2]. However, there has been little systematic study of REE-Li in lateritic granite rocks in Indonesia despite the extensive distribution of granitoids across the country. Therefore, this review explores the presences of REE-Li in clays associated with granitoid and speculates on the potential discovery of new deposits in laterite granite – a direction in which efforts need to be intensified.

2. Characteristics of potential REE-Li in weathered granite
REE-Li is known to be richest during the differentiation process of magma in mantle melts. REE-Li can also be richly concentrated in granitoids, which accumulate as mineral accessories such as titanite,
allanite, apatite, monazite, xenotime, zircon, amblygonite, lepidolite, petalite, and zinnwaldite, because these elements tend to remain melted until the final stage of magma differentiation [3 - 4]. However, the main minerals present in granite are mega crystals of quartz, biotite, plagioclase, k-feldspar and hornblende [5].

Ionic radii affect the partitioning of trivalent rare-earth elements (REE$^{3+}$), which decreases with an increase in atomic number because the ionic radius of the ions becomes larger (Figure 1) and their adsorption is regulated by characteristics such as solution pH, ionic strength, and the clay minerals present [6]. REE deposits via ion-adsorption occur in tropical climates through the following processes: (a) REE are washed off from granites by groundwater, (b) a bold layer of laterite zones with clay-rich content develops above the granites, and (c) the mobilized REE ions are gradually absorbed onto the clays in the lateritic granite zones [7].

![Graph of the ionic radius of rare-earth ions ($^{3+}$), cerium ($^{4+}$), and europium ($^{2+}$) [7]](image)

The REE ion-adsorption deposits from weathered granite comprise the REE accumulation zone in the lower profile, and the REE leached zone is in the upper profile. The REE leached zone exhibits a positive Ce anomaly resulting from the oxidation of Ce$^{3+}$ to Ce$^{4+}$. Nonetheless, the REE accumulation zone, specifically the thick REE ion-adsorption zones, exhibits a negative Ce anomaly due to the other REE$^{3+}$ ions that are specially adsorbed onto clays. Consequently, the negative Ce anomaly in the ion-adsorption ores has a positive correlation with the ion-exchangeable REE concentration, and this anomaly is a useful indicator in geochemical exploration [2].

Lithium was leached easily during weathering even though sedimentary environments have no sedimentary minerals enriched lithium either than clay minerals. In minerals, univalent lithium can replacement to a degree for divalent magnesium and iron, but its smaller ionic size does no longer allow its substitution to any substantial volume with chemically associated extra-plentiful alkalis, sodium, and potassium. All common cations can dislodge Li$^+$ from base exchange material; consequently, base-exchange reactions tend to deliver lithium into solution [8].

3. REE-Li ion adsorption in weathered granite

In southern China, concentrations of REE ion-adsorption deposits vary roughly from 500 to 2000 parts per million (ppm), with lower concentration in the parent granites or bedrocks [9]. The largest REE deposits are typically found in the B horizon of the lateritic granite zone. In addition to having the highest concentration of REE ion-adsorption deposits, the B horizon also has an abundances of clay minerals. In the upper zone of the lateritic granite profiles, the A horizon is enriched with organic matter and clay minerals, while the C horizon comprises fragments of half-weathered granites and clay minerals.
Lateritic granite has been identified in Jiangxi, China, with REY (REE + Y) grade deposits varying from 143 to 1228 ppm [2]. However, Mamasa and Palu granite enriched with REE ion-adsorption deposits are typically found in the B horizon, with REE concentrations of up to 314 ppm. Studies on this region have reported that the REE contents are dramatically depleted in the A horizon, while the B horizon has deposits approximately 70% to 85% richer than the parent granites. These findings indicate that the REE ion-adsorption enrichment occurred in the B horizon [10]. Although REE ion-adsorption deposits in lateritic granite contain low-grade REE minerals (500-2000 ppm of REE₂O₃), in comparison with other deposit types, they are of interest as an exploration target because of their extensive areal distribution, low mining costs, and the low Th and U content of the ores in this zone. [11].

Some muscovite-bearing granites have been identified as lithium-enriched granites, including zones enriched with lithium, tin, fluorine, and tantalum. The peak of a biotite-muscovite granite at the Yichun Mine in Jiangxi, China, transforms into muscovite granite and lepidolite granite, which has been mined for lithium and tantalum [12]. In addition to the weathering process removing lithium from Li-bearing minerals, it incorporates the lithium into clay minerals. Previous studies have reported lithium content in clay minerals with concentrations ranging from 7 ppm to as high as 6000 ppm in hectorites [13]. In humid climates, lithium tends to be concentrated in kaolinite in bauxite, in which lithium concentrations of 340 ppm have been recorded [13]. Nonetheless, Li in lateritic granite is not easily identified. According to Ronov et al. [14], kaolinite from granodiorite contains Li in concentrations of about 45 ppm, which increases slightly to as much as 118 ppm for kaolinite derived from amphibolite. However, studies on kaolinites have compared altered schists and granites, with results showing that there is more lithium in kaolinites from granites than that in kaolinites from schists [13].

4. Areas with potential REE-Li sources in Indonesian granitoids

Based on the literature, granitoid rocks that are widespread in Indonesia, especially on the Bangka Belitung Islands and West Kalimantan are generally associated with high radioactive values, while the West Sulawesi area commonly has high radioactive values from volcanic rock formations (Figure 2). According to Gill [15], granitoid rocks are grouped into diorites, tonalites, granodiorites, granites, and alkaline granites based on mineralogy, with specific tectonic conditions producing a distinct granitoid rock.

![Figure 2](image-url)
The Bangka Belitung Islands are composed of main range granitoid and eastern granitoid. Main range granitoid is biotite-monzogranite with an S-type chemical composition associated with Sn, Fe, W, and REE, while eastern granitoid is biotite and biotite-hornblende of monzogranite, which have an I-type chemical composition. West Kalimantan has the Natuna-Sanggau and the Schwaner Mountains complex of granite, granodiorite, diorite, and tonalite. This complex is replete with minerals such as biotite pyroxene, quartz, hornblende, orthoclase, and plagioclase. West Sulawesi has the Mamasa granitic rocks of granite, granodiorite, diorite, and quartz monzonite, and has the Palu granitic rocks of monzonite and granodiorite [10]. The main mineral composition includes biotite, hornblende, and quartz, which are grouped into an ilmenite series in the south zone, an ilmenite-magnetite series in the middle zone, and a magnetite series in the north zone. Granitic rocks in West Sulawesi are associated with Cu, Au, Mo, REE, and radioactive elements [17].

Overall, Indonesia has an extensive distribution of granitoids located in a tropical climate; therefore, it has potential REE-Li resources in clay deposits. The weatherable REE-Li bearing minerals are the sources of ion-exchangeable deposits absorbed onto clay minerals.

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