Sains Malaysiana 54(11)(2025): 2577-2588
http://doi.org/10.17576/jsm-2025-5411-01

A Review of Rare Earth Elements in the Western Belt of Peninsular Malaysia

(Tinjauan Unsur Nadir Bumi di Jalur Barat Semenanjung Malaysia)

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Received: 19 August 2024/Accepted: 29 October 2025

ABSTRACT

Rare Earth Elements (REEs) alternatively termed non-energy minerals, have emerged as a greatly coveted resource for industries focused on high-technology and low-carbon applications. The Western Belt of Peninsular Malaysia has the potential to yield ion-adsorption rare earth element (REE) clays, which are found in extensive weathered granitic crusts that frequently exhibit high-grade ion-adsorbed REEs. Currently, global demand is increasing, and there are concerns over future availability. Malaysia is also recognized as a country with significant REEs material production, along with the United States, Australia, Brazil, India, Russia, Thailand, and Vietnam. This paper has two main objectives, which were; i) to conduct a literature review related to REE in the Western Belt and ii) to identify distribution pattern of REE deposits in Western Belt of Peninsular Malaysia. The methodology for this paper is all the data collected from ranges of sources including geological surveys, academic literature, and industry reports. Sites were selected based on their geological characteristics and historical data indicating the presence of REE mineralization. This extensive review also highlights the geochemistry, geological setting, exploration and extraction associated with REEs in the Western Belt of Peninsular Malaysia. The insights presented here can aid the government, researchers, and decision-makers in gaining a better understanding of REEs, enabling them to continue producing rare earth-dependent products and meeting global demand.

Keywords: Global demand; non-energy minerals; rare earth elements (REEs); Western Belt; Peninsular Malaysia

ABSTRAK

Unsur Nadir Bumi (REE) dikenali sebagai mineral bukan tenaga, telah muncul sebagai sumber yang sangat dicari oleh industri yang berfokus kepada teknologi tinggi dan aplikasi rendah kandungan karbon. Jalur Barat Semenanjung Malaysia mempunyai potensi unsur nadir bumi (REE) jerapan ion dan ia banyak ditemui dalam batuan granit yang mengandungi unsur nadir bumi yang berkualiti tinggi. Kini, permintaan global semakin meningkat dan terdapat kebimbangan terhadap keperluan pada masa hadapan. Malaysia juga diiktiraf sebagai negara yang mempunyai pengeluaran bahan REE seiring bersama dengan negara seperti Amerika Syarikat, Australia, Brazil, India, Rusia, Thailand dan Vietnam. Kertas ini mempunyai dua objektif utama, iaitu; i) untuk menjalankan kajian kepustakaan berkaitan REE di Jalur Barat dan ii) untuk mengenal pasti corak taburan REE di Jalur Barat Semenanjung Malaysia. Kaedah yang digunakan untuk kertas ini adalah pengumpulan semua data daripada pelbagai sumber termasuk kajian geologi, kajian kepustakaan dan laporan industri. Kawasan kajian dipilih berdasarkan ciri geologi dan data terdahulu yang menunjukkan kehadiran pemineralan REE. Kajian ini juga menekankan kajian geokimia, maklumat geologi, penerokaan dan pengekstrakan yang berkaitan dengan REE di Jalur Barat Semenanjung Malaysia. Kajian ini akan membantu kerajaan, penyelidik dan pembuat dasar dalam memahami REE dengan lebih baik, menghasilkan produk yang berasaskan kepada unsur nadir bumi dalam memenuhi permintaan global.

Kata kunci: Permintaan global; mineral bukan tenaga; unsur nadir bumi (REE); Jalur Barat; Semenanjung Malaysia

INTRODUCTION

The rare earth minerals present in weathered crust elution-deposited ores have captured worldwide interest due to their significant value as a resource (Zhang et al. 2016). Rare earth elements (REEs), also known as rare earth metals (REMs), comprise a group of seventeen chemical elements located in the periodic table, spanning from lanthanum (57La) with atomic number 57 to lutetium (71Lu) with atomic number 71, along with scandium (21Sc) and yttrium (39Y). Scandium and yttrium are rare earth elements because they frequently occur in the same ore deposits as lanthanides and exhibit similar chemical characteristics (Shafiee, Achmad Bahar & Ali Khan 2020). The REEs are silver-white metals, typically in the 3+ oxidation state, and possessing high electrical conductivity (Voncken 2016). Due to their distinct magnetic, phosphorescent, and catalytic properties, REEs have gained significant usage in the high-technology and clean-energy industries (Balaram 2019). The REEs are widely used in digital technology, medical fields, energy efficiency applications, electric and hybrid vehicles, environmental applications, military applications, and permanent magnets that are used in a larger number of different applications (Alnour et al. 2015; Schreiber, Marx & Zapp 2021; Zepf 2013). The estimated end-use distributions of rare earth are 74% for catalysts, 10% for ceramics and glass, 6% for metallurgical applications and alloy, 4% for polishing, and 6% for others (Cordier 2022).

There are currently 120 million tonnes of REE reserves in the world (US Geological Survey 2022). The highest known REE reserves are in China with 44,000,000 tonnes (36.67%), followed by Brazil and Vietnam respectively with 21,000,000 tonnes (17.5%) and then by Russia with 19,000,000 tonnes (15.83%). According to Cordier (2022), the mine production of rare earths in Malaysia was 180 tonnes and 200 tonnes for 2017 and 2018; respectively. Despite this, Malaysia has become a leading supplier of rare earth compounds outside of China (Gambogi 2018) due to Malaysia's production of mineral concentrates from Australia. The Malaysian Investment Development Authority (MIDA) has stated that the New Industrial Master Plan (NIMP) 2030 highlights the potential of rare earth elements (REE) and aims to capitalize on 18.2 million tonnes of non-radioactive REE reserves by 2030. As mentioned in Alnour et al. (2015), the literature on REEs data in Malaysian rocks, particularly in granite, is limited. Therefore, this review paper provides comprehensive information on the REEs found in the Western Belt of Peninsular Malaysia. This review paper's primary goals are to provide an overview of REE and identify distribution pattern of REE deposits in Western Belt of Peninsular Malaysia.

THE GEOCHEMISTRY OF REE's

REEs have been recognized as valuable because of their unusual chemical and physical properties. The REEs are categorized into two sub-groups: the first sub-group comprises the lighter elements from lanthanum (La) to europium (Eu), known as the light rare earth elements (LREE). The second sub-group comprises the heavier elements from gadolinium (Gd) to lutetium (Lu) and yttrium (Y), known as the heavy rare earth elements (HREE). According to Kanazawa and Kamitani (2006), the difference between light rare earth elements (LREEs) and heavy rare earth elements (HREEs) is based on their atomic number. The Oddo-Harkins effect causes rare earth elements with even atomic numbers to be more abundant than those with odd atomic numbers. In addition, the LREE have larger ionic radii and therefore are more incompatible, resulting in a higher concentration in the continental crust compared to their heavier counterparts with larger atomic numbers. The similar chemical properties of the rare earth elements, such as their ionic radii and oxidation states, enable them to replace one another within crystal structures (Shafiee, Achmad Bahar & Ali Khan 2020).

Rare earth elements (REEs) also tend to be transported from their source to their destination without significant fractionation due to their high insolubility in aqueous solutions (Balashov et al. 1964; Lee et al. 2014). In general, LREEs are more abundant in carbonates and phosphates, while HREEs are more abundant in oxides and a subset of phosphates. The LREEs are generally more soluble in water, which makes them more likely to be transported by groundwater and deposited in sedimentary rocks. Some examples of LREE minerals include bastnäsite, monazite, and xenotime. For the HREEs, they are more commonly found in minerals such as oxides and a small fraction of phosphates. These minerals are less soluble in water, which means they are less likely to be transported by groundwater and more likely to be found in igneous or metamorphic rocks. Some examples of HREE minerals include xenotime, gadolinite, samarskite, and euxenite. According to Laveuf and Cornu (2009) and Zhu and Liu (1988) which has been reported in Mihajlovic et al. (2019), phosphates exhibit high concentrations of REE, carbonates have low REE content, while silicates show a broad range of REE content.

Additionally, the REE content in Chinese soils decreases in the following order based on the source material: Granite > Quaternary > Basalt > Sandstone. Detailed studies by Umor et al. (2011) also found that the Western Belt granitoids are primarily categorized as peraluminous granites, and they are predominantly classified as S-type granites with minor occurrences of I-type granites. Most of the global supply of rare earth elements (REEs), particularly heavy rare earth elements (HREEs), is obtained from ion adsorption deposits, also known as weathered crust elution deposits. This is mainly due to HREEs being commonly found bound with Yttrium (Y) in geochemical associations, and these deposits have traditionally been the primary source of REE mining. The rare earth ore deposit resulting from weathered crust elution can be classified into four distinct layers: the humid layer, the completely weathered layer, the partially weathered layer, and the bedrock (Zhang et al. 2016).

Based on the study by Yaraghi et al. (2020), weathered granitic profiles from two sites within the Malaysian Western granite belt, namely Lumut (LU) and Telok Murok (TM) show their potential as sources of rare earth elements (REEs) in conjunction with ion-adsorption clays. Both sites displayed identical petrographic properties, however, the prevalent clay minerals in the profiles varied due to the differences in geochemical composition and alteration conditions. The results also showed the weathered crust of granitic rocks was thicker in the LU site compared to the TM site, however LU site exhibited the highest concentration of REY at 2360 ppm. In both sites, the enrichment of REEs took place in the lower part of the profiles, specifically in horizons B2 and C, owing to the distribution pattern of clay minerals within the profile.

The humic layer is the primary source of exchangeable aluminium in the rare earth ore deposited in the elution of the weathered crust. On the other hand, the totally and partially weathered layers are rich in rare earth elements, with the light rare earth group dominating the humic layer. As a result, mining rare earth from the humic layer may not be financially feasible. Zhang et al. (2016) also discovered that clay mineral swelling in the humic layer ranged between 2.5% and 2.7%, which was greater than swelling in the completely weathered and partially weathered layers. Ion-adsorption REE deposits are formed when clay minerals with a high cation exchange capacity (CEC) absorb and accumulate REE^{3+} ions (Li et al. 2017; Sanematsu, Kon & Imai 2015). The abundance of rare earth elements in various forms increases in the following order: ion-exchangeable state> mineral state> colloid sediment state> aqueous soluble state. The ion-exchangeability of rare earth elements are bonded onto clay minerals as hydrated or hydroxyl-hydrated cations (Chi & Tian 2008; Zhang et al. 2016).

The study by Aide and Aide (2012) also found that the REEs are commonly observed in parent materials ranging from 0.1 to 100 ppm and this indicates that their levels are moderate when compared to other trace elements. According to Mihajlovic et al. (2019), the REE composition appears to be impacted by the parent material's regional origin, degree of weathering, and soil type. The study by Yaraghi, Ariffin and Baharun (2020) also proposed that surface CO_2 and humic chemicals, when coupled with surface and groundwater, provide an acidic environment that dissolves bedrock minerals. According to Bao and Zhao (2008), the accessory minerals such as bastnaesite, parisite, gadolinite, doverite, allanite, xenotime, monazite, zircon, and apatite carry 24% to 28% of the total REEs in granitic rocks from southeastern China. The REEs abundant in some granitic accessory minerals are frequently released as trivalent ions due to acidic dissolution and migrate to the lower parts of weather-ing profiles in complex forms with groundwater (except Ce, which tends to precipitate as cerianite). According to Aide and Aide (2012), rhyolites and granites have larger concentrations of REEs than basalts and peridotites, with LREEs exhibiting much higher levels than HREEs. Argillaceous sediments and shales usually have more REEs than limestones and sandstones. Similar to igneous materials, sedimentary materials have higher quantities of LREEs than HREEs. The REE content increases with decreasing particle size and increasing percentage of the clay-size fraction. Clay minerals may hold REEs and act as transporters for them. Therefore, clayey soils have high REE concentrations (Mihajlovic et al. 2019).

The study by Zhang et al. (2018) also showed the concentration of rare earth elements (REEs) in the weathered orebody at different depths. Figure 1 shows the topography locations of REE enrichment zone.

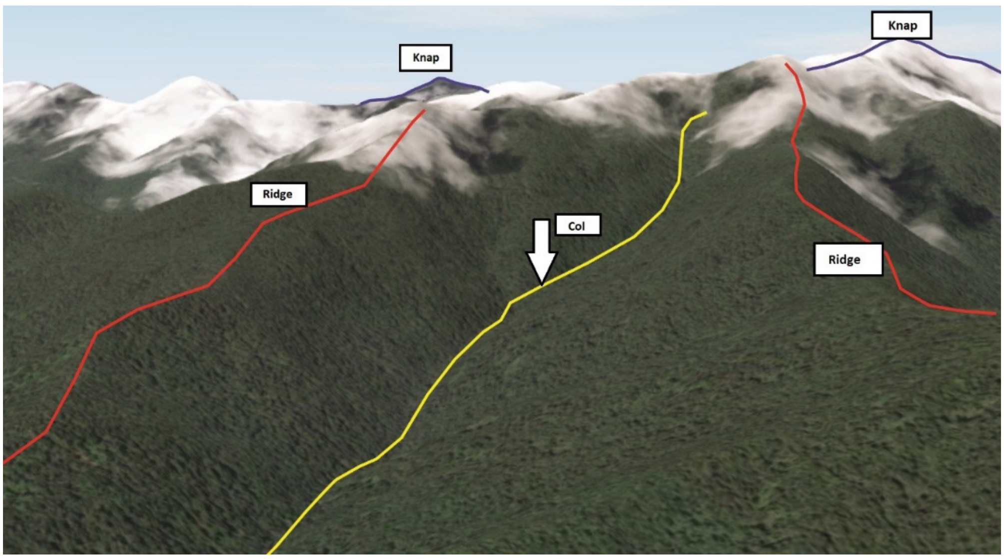

FIGURE 1. REE-enriched zone in a weathered orebody (Modified from Google Earth 2025 and Zhang et al. 2018)

According to their studies, when comparing different terrains of the weathered orebody, they discovered no significant differences in rare earth composition in the humic layer. However, the sequence of rare earth element contents in the totally and partially weathered layers was as follows: REEcol > REEknap > REEridge. Rare earth ions were transported by groundwater and exhibited larger concentrations in the col area due to the continual adsorption and desorption process. This higher abundance in the col area can be attributed to its location in the weathered orebody's lower terrain. The HREEs are also rich in lower terrain of weathered orebody. Their studies also approached the REEs in col weathered crust elution-deposited rare earth ores due to the concentration of HREEs and higher economic value.

GEOLOGICAL SETTING

Peninsular Malaysia was formed in the Early Triassic - Middle Triassic and is located at the centre of Southeast Asia. A collision between the Sibumasu Block in the West and the East Malaya Block formed the Peninsular Malaysia which has been divided by the Bentong Raub Suture (Metcalfe 2000). Peninsular Malaysia is divided into three parts, namely the Western Belt, the Central Belt, and the Eastern Belt based on stratigraphy by Khoo and Tan (1983). The Western Belt is part of the Sibumasu Block. Metcalfe (1988) states that the Sibumasu Block consists of the Shan State of Burma, northwestern Thailand, Peninsular Burma and Thailand, Western Peninsular Malaysia, and northwestern Sumatra. A sequence of Lower Paleozoic rocks characterizes this block and has bands of Late Carboniferous - Early Permian marine glacial diamictites (Khoo & Tan 1983; Metcalfe 1988; Stauffer & Lee 1986) divided the Western Belt into two parts, the north-west and the Kinta - Melaka sector in the south of the Western Belt. Kedah, Perlis, and north Perak compromise the northwestern part of the Western Belt. The rock formations in the northwest are composed of clastic, limestones, and minor volcanic (Khoo & Tan 1983). While in the Kinta-Malacca areas, the argillaceous and calcareous sediments from the early Paleozoic were deposited, followed by limestone deposition in the Kinta Valley and clastic deposition in the Kuala Lumpur area. The Central Block and the Eastern Block of Peninsular Malaysia are part of the East Malaya Block. The geology of the East Malaya Block consists of a sequence of sedimentary rocks of middle to late Paleozoic age and are shallow to marine deposits. This sequence is overlain by shallow-marine to deep-marine volcanic and volcaniclastic rocks of Permian-Triassic age and Late Mesozoic red-bed sediments. Late Triassic and Cretaceous age granite intruded the earlier rock formations and Quaternary age alluvial sediments deposited along the east coast of Peninsular Malaysia (Basori et al. 2018).

The Peninsular Malaysian granites have been divided into two granite provinces. The Western Belt is composed of Main Range Granites with an age range of 200 to 230 Ma while the Eastern province of Peninsular Malaysia consists of granites from both the Eastern and Central Belts, with an age range of 200 to 264 Ma (Cobbing et al. 1992). A suite of tin-bearing S-type granite is present in the huge batholiths or complex plutons that make up the Western belt granites. It encompasses an area larger than 15,000 km^2, forming a massive mountain range that stretches from Thailand in the north to Malacca in the south. The Western Belt Granite can be divided into two primary batholith masses. These include the nearby Bintang batholith to the west and the Main Range batholith on the eastern edge (Ghani 2005). The granitoid of the Western Belt are predominantly granite, peraluminous with a high-K calc-alkali series and S-type granite affinity, and were intruded in a syn-collision or post-collision environment (Umor et al. 2011). The granites of Langkawi feature an intermediate microcline content, and the rocks of the Carboniferous Singa Formation show a prominent contact metamorphic aureole. The rocks are metamorphosed outside the aureole contact (Hutchison 1977; Spiller 2002). According to Makoundi et al. (2021), mudstones from the Singa Formation contain lonestones, or ice-rafted dropstones, indicating that they were created by glaciers. The researchers also discovered that early sedimentary pyrites in pebbly mudstones contain high levels of gold and other trace metals. The REE elements detected were Y, Sc, La, and Nd, with concentrations ranging from 28.10 to 34.30 ppm, 12.05 to 16.20 ppm, 33.90-49.34 ppm, and 31.30-41.20 ppm, respectively.

The Eastern Belt Granite, which is located east of the Bentong Raub line, is made up of smaller batholiths of zoned and unzone plutons of compositionally expanded monzogranite with I type affinities. Base metal deposits that are found within and in the marginal zones of some plutons make up the majority of the mineralization in the Eastern Province (Ghani 2005). In Peninsular Malaysia, biotite granite and hornblende biotite granite make up the majority of the granitoids. While hornblende biotite granite primarily outcrops in the Eastern and Central belts, biotite granites are primarily distributed in the Western belt with a slight distribution in the Eastern belt and were thought to have S-type affinity (Cobbing et al. 1992; Ng et al. 2015). It was believed that hornblende biotite granites had I-type affinity and were unrelated to tin mineralization (Ng et al. 2015).

THE PRINCIPAL REE DEPOSITS IN MALAYSIA

Several types of REE deposits have been studied and mined from all around the world. From comprehensive review of literature on REE occurrences in Malaysia, this study classifies REE deposits into seven categories: (i) alkaline igneous rocks, (ii) pegmatites, (iii) placer deposits containing monazite and xenotime, (iv) marine sediments, (v) river and lake sediments, (vi) ion-adsorption clays linked to weathering crusts, and (vii) shale and coal deposits (Balaram 2025; Syed Muhammad Ibad 2024). However, there are three main sources of REEs mainly; igneous rocks, sedimentary deposits (placer deposits and conglomerate), and secondary sources (ion - adsorption clay deposits). In Malaysia, REEs have been exploited from monazite and xenotime placer deposits as a byproduct of tin mining. The REEs from igneous sources originate from hydrothermal activity, carbonatite rocks, alkaline rocks, and alkaline granites. Peninsular Malaysia does not have the geology and tectonic settings favorable for the traditional alkaline igneous and carbonatite-type rare earth deposits. These deposits are formed by the process of hydrothermal replacement of carbonate sedimentary rocks, but the hydro-thermal fluids may have originated from a series of alkaline-carbonatite intrusives (Kanazawa & Kamitani 2006). Most of the REEs in granite and other igneous rocks are concentrated in the formation phase of accessory minerals such as allanite, monazite, and zircon and minor accessory minerals consisting of apatite, thorite, and ilmenite with some magnetite (Bao & Zhao 2008; Sanematsu et al. 2013).

The REEs from sedimentary sources are formed as placer deposits. The main REE minerals are monazite and xenotime. In Malaysia, tin mining produces amang containing small amounts of cassiterite waste, sand, and heavy minerals consisting of ilmenite, zircon, monazite, xenotime, columbite, rutile, and struvite. Monazite and xenotime have been the by-product from alluvial tin mining in Peninsular Malaysia since 1900s (Willbourn 1925). Due to the steady oxidation of REEs, Malaysian monazite typically has reasonably well-rounded discrete or as some portions with color ranging from transparent, rich canary yellow through cream-colored with resinous sheen (Flinter, Butler & Harral 1963; Wan Hassan 1989). The Jerai monazite has unusually long, rolled grains with a flattened structure and a vivid green color (Flinter, Butler & Harral 1963; Wan Hassan 1989). According to Wan Hassan (1989), the xenotime crystal habit is distinct in that it has a double pyramidal termination on a prism in the Malaysian Eastern Belt and a squat tetragonal bipyramid on a prism in the Malaysian Tin Belt.

The REE deposits from secondary sources form in the weathering profile of residual granite and are contained in ion-adsorbed clays. Weathered granite contains some adsorptive weathering products that can adsorb positively charged REE ions and complexes. Adsorption of REEs in weathered granite is controlled by the type of adsorbent such as clay (kaolinite and halloysite), goethite (Fe hydroxide), bauxite (Al hydroxide), and the pH of the groundwater (Sanematsu et al. 2013). In 2013, a Japanese Geologist started to collect some soil samples from weathered granite in the Bukit Tinggi areas for REE analysis. Beginning in 2014, the Malaysian Department of Mineral and Geoscience (JMG) began investigating ion-adsorption clays in granite-underlain regions of Perak, Terengganu, Pahang, and Johor.

DISTRIBUTION OF REEs IN WESTERN BELT, PENINSULAR MALAYSIA

The Western Belt of Malaysia, which is sometimes referred to as the Tin Belt, is recognized for its abundant reserves of Rare Earth Elements (REEs). The distribution pattern of REEs in Peninsular Malaysia are illustrated using Table 1 and Figure 2. From the distribution pattern of REE's, study shows that granites in Western Belt of Malaysia has a clear enrichment in light REEs (LREEs) over heavy REEs (HREEs), with (La/Yb)cn values typically ranging from 2.59 to over 22, indicating pronounced LREE dominance. This geochemical signature is typical of S-type granites derived from crustal sources and suggests fractional crystallization and feldspar retention during magma evolution. The TREE values also vary widely from low (110 ppm) in Langkawi granites to high (up to 369 ppm) in the Bukit Mertajam/Kulim batholith. Negative Eu anomalies (Eu/Sm ratios from 0.01 to 0.17) are consistently observed, suggesting plagioclase fractionation or retention during crystallization, which is typical for evolved granitic magmas. While for other egions such as Kledang and Penang exhibit stronger negative Eu anomalies and higher ΣREE contents, suggesting a more evolved magmatic history.

CURRENT PRACTICE OF REE IN MALAYSIA

According to Balaram (2025), extracting REE's collectively from various ores and sources is relatively straightforward, but isolating them individually is challenging due to their highly similar physical and chemical properties. The ore deposits with physically adsorbed REEs typically have lower grades compared to other REE deposit types, they remain economically viable due to their low extraction and processing costs, along with safer and simpler mining operations, largely owing to the minimal presence of radioactive elements (Rukayah et al. 2024). There are two types of rare earth extraction: open-pit mining and *in-situ* leaching technology. Previous researchers Paraschi and Poulaki (2021) stated that rare earth mineral extraction usually uses open-pit mining. Underground mining is required to extract rare earth minerals. The mined ore is crushed and ground to generate fine powder in the mill, to provide a high surface area required for further separation. The most common method for this separation is flotation. However, it uses a lot of water, chemicals, and energy. The input for flotation is the milled crude ore, which usually has low concentrations of rare earth oxides (REO). The output of flotation is an enriched concentrate with a higher percentage of rare earth elements (REE). The waste material produced in this process, known as tailings, is a mix of water, processed chemicals, and finely ground minerals. These tailings are housed in containment areas, often in man-made reservoirs, with concentrations of approximately 500 parts per million (ppm) of thorium oxide and 30 ppm of uranium oxide. The concentrated material undergoes additional processing to extract the rare earth elements. Within the refinery, these elements are then separated into their individual components as required. The Mount Weld rare earth mine in Australia illustrates an open-pit mining operation targeting ore with an average REO grade of 15%. Subsequently, these minerals undergo

TABLE 1. The distribution pattern of REEs in the Western Belt of Malaysia

REE sources / deposit	Location	Formation/Lithology	Age	Description/Estimated resources	References
Igneous (Granite)	Pulau Langkawi, Kedah	• Granite batholiths forming Gunung Raya, PulauTuba, Pulau Bumbon and part of Pulau Dayang Bunting • Medium to coarse-grained highly porphyritic biotite granite	Late Triassic	• REE curves shows a general enrichment of the LREE components followed by low HREE components with $(La/Yb)_{cn}$ values from 2.59 to 10.79 • ΣREE content is low (110-232 ppm)	Wan Hassan & Hamzah (1999)
	Penang	• Penang granite, ranging from adamellite to leucogranite, has been divided into two suites; Bukit Bendera and Sungai Ara suites (Liew 1983)	Late Triassic	• Higher ΣREE contents from 209 to 230 ppm • Show similar enrichment of LREE component with (La/Yb>en values from 4.55 to 10.05 and have moderately strong negative Eu anomalies with Eu/Sm ratios from 0.08 to 0.12	Wan Hassan & Hamzah (1999)
	Penang	• Bukit Mertajam batholith, on the mainland known as Kulim batholith. • This batholith is recognized as belonging to two suites; Penanti and Bongsu suite (Courtier 1974)	Late Triassic	• Similar LREE enrichment is observed, with (La/Yb) values from 8.80 to 22.33 • The ΣREE content have are from 165 to 369 ppm • Negative Eu anomali with Eu/Sm ratios from 0.09 to 0.17	Wan Hassan & Hamzah (1999)
	Taiping, Perak	• Bintang batholith or the Bubu suite of Liew (1983) • The rock is predominantly coarse-grained porphyritic adamellite granite • Taiping granite is associated with tin mineralization	Late Triassic	• Enrichment of the LREE components with (La/Yb)cn values from 4.60 to 17.82 • Their lREE content is comparable to those of Penang and Kulim with values from 143 to 362 ppm • Negative Eu anomalies are clearly seen	Wan Hassan & Hamzah (1999)
	Kledang, Perak	• Kledang Range granite is grey, medium-grained, fairly porphyritic biotite granite • Kledang Range granite is associated with tin mineralisation in Kinta Valley	late Triassic	• Strong negative Eu anomalies, with EulSm 0.01 to 0.07 • ΣREE content is relatively high, ranging from 278 to 328 ppm • REE enrichment is not pronounced and have $(La/Yb)_{cn}$ relatively lower with values mainly about 2	Wan Hassan & Hamzah (1999)

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	Cameron Highland, Pahang	• Main Range granites • Grey, medium – grained, moderately porphyritic biotite granite	Late Triassic	• ΣREE is 203 to 249 ppm with LREE enrichment $(La/Yb)_{cn}$ from 4.9 to 11.07	Wan Hassan & Hamzah (1999)
	Kuala Lumpur	• Main Range granites divided into two suites, Beranang Suite and Ulu Kali Suite • Composed of biotite granodiorite to muscovite leucogranite	Late Triassic	• ΣREE is 119 to 361 ppm	Wan Hassan & Hamzah (1999)
	Kuala Pilah, Pahang	• Southern part of Main Range granite from Tampin batholith	Late Triassic	• This granite exhibits a typical lREE pattern with LREE enrichment (LaIYb)cn 7.82-10.52 and mild to moderate negative Eu (EulSm 0.08-0.12)	Wan Hassan & Hamzah (1999)
	Batang, Melaka	• Southern part of West CoastProvince	Late Triassic	• Batang Melaka have ΣREE 106-132 ppm) • They are high in LREE components but low in HREE, with (LaIYb)cn values ranging from 7.40 to 20.06	Wan Hassan & Hamzah (1999)
Monazite – Xenotime Bearing Placer Deposit	Jerai, Kedah	• Granitic bedrock, metasedimentary bedrocks, and unconsolidated deposits	Late Triassic	• Th content samples ranges from 74.6 ppm to 1,530.0 ppm. The U content ranges from 48.5 ppm to 1,553.0 ppm. The Sc content ranges from 16.5 ppm to 87.8 ppm while the Y content ranges from 266.0 ppm to 7,604.0 ppm • TREE content ranges from 928 ppm to 21,031 ppm • The THREE content ranges from 411 ppm to 11,435 while the TLREE content ranges from 517 ppm to 9,596 ppm	Fauzi et al. (2021)
Ion – adsorption clay deposits	Bukit Enggang Granite, Kedah	• Granite soil/ bedrock	Late Permian to Triassic	• The average REE content in rock samples ranges from 206.70 ppm to 475.07 ppm • The TREE of granite soil ranges from 432 to 1,455 ppm	Fakhruddin et al. (2023)
Ion – adsorption clay deposits	Dinding Region within the Bintang Granite Range in Perak	• Medium-grained mica (phlogopite)-rich, S-type, peraluminous, ilmenite-series granite with metamict texture	Late Triassic	• High amount of REY (2360 ppm) • HREE-rich prospected area	Yaraghi, Ariffin & Baharun (2020)
Granitic igneous bodies	South Perak		Late Triassic	• The total REEs content (TREE) exceeds the minimum threshold value of 300 ppm	Ahmed et al. (2023)

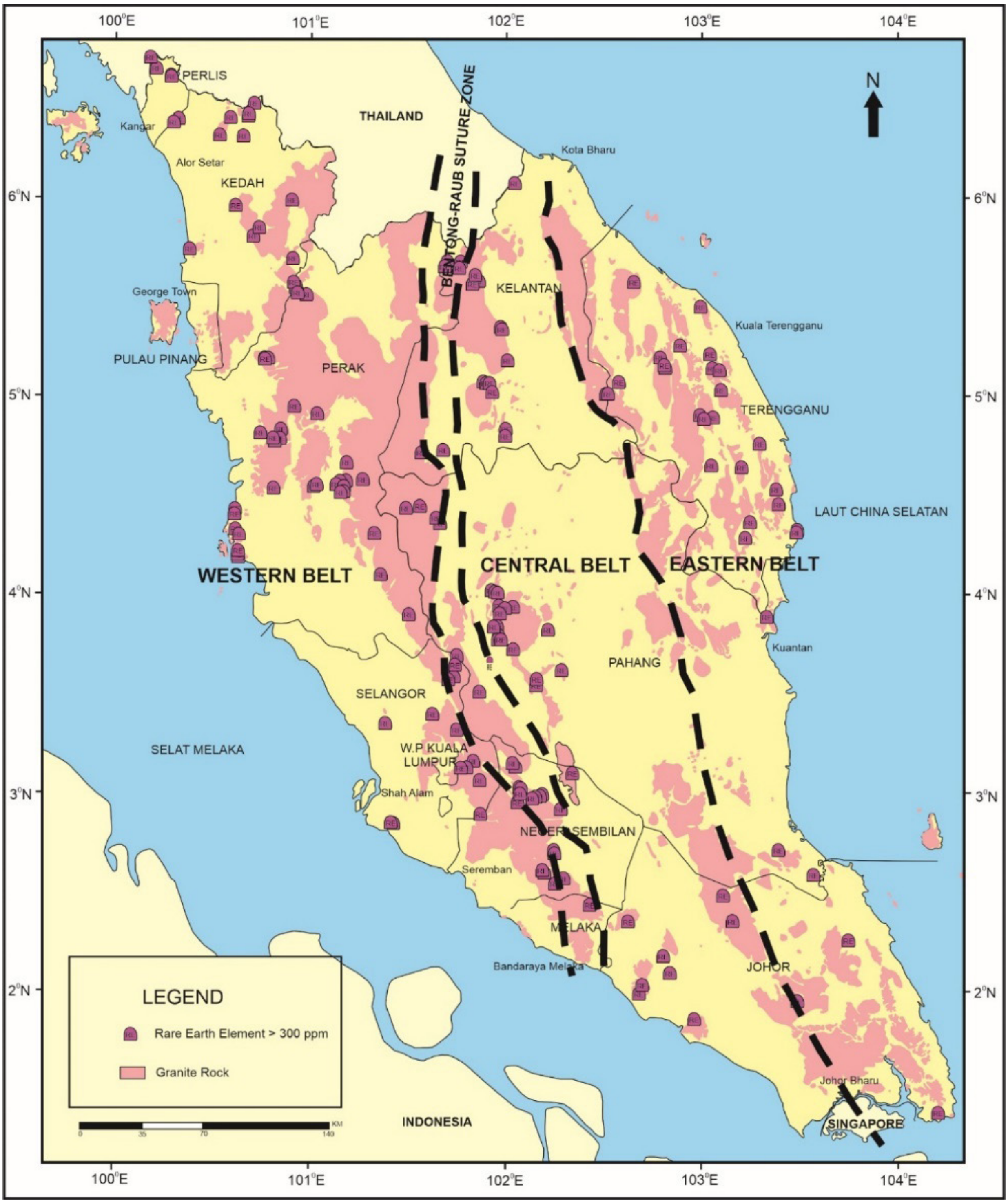

FIGURE 2. Simplified distribution of REE in Peninsular Malaysia

processing at a concentration plant to reach a concentration level of 40%. The Lynas Corporation of Australia has established the largest extraction plant globally in Gebeng, Malaysia, close to the city of Kuantan. This plant extracts approximately 22,000 tonnes of rare earth from minerals transported from Mount Weld, Western Australia (Paraschi & Poulaki 2021; Phua & Velu 2012).

Another mining technology used in China heavy rare earth element (HREE) mining from ion adsorption clay through *in-situ* leaching (Paraschi & Poulaki 2021). The use of *in-situ* leaching to solve the environmental challenges associated with rare earth mining and extraction remains a hotly debated topic. Clark and Zheng (1991) and Kanazawa and Kamitani (2006) stated that ion-adsorption rare earth deposits are commonly found in granitic rocks of Yanshanian age (195-130 million years ago). These granites, located in warm, moist subtropical zones, have undergone significant chemical and biological weathering. During this process, rare earth elements (REEs) have been absorbed into clay minerals on the rock's surface in an ionic state, forming ion-adsorption type REE deposits. Two main conditions are necessary for the formation of these deposits; i) there must be enough REE-bearing host rock, and ii) the weathering and lateritic processes must be preserved over a long period without significant erosion. The study by Zhang et al. (2018) also discovered that the chemical leaching technology is the only method for extracting rare earth elements and ammonium salt/ammonium sulphate is utilized in this chemical reaction.

The initiation of the first rare earth mining project in Mukim Kenering, Hulu Perak, Malaysia marks a significant milestone in the region's mineral extraction industry. The Director of the Department of Minerals and Geoscience (JMG) has confirmed the first pilot project for *in-situ* leaching to mine non-radioactive rare earth elements (FMT 2023). The pilot project is implemented in compliance with standard operating procedures. Ion adsorption clay deposits, formed through the weathering of REE-rich granite rocks, exhibit a distinct mechanism wherein rare earth elements are leached from the parent rock and subsequently adsorbed onto clay minerals in the soil. The *in-situ* leaching method uses a low-concentration of ammonium sulfate solution injected into the soil to extract rare earth elements through ion exchange. The minerals flowed through a pipe system and were collected at the hill's base for further processing. However, this method is only suitable for REE minerals found above the groundwater level to ensure effective leaching and prevent groundwater contamination. According to Zhang et al. (2018), there are two main concerns in developing an *in-situ* leaching process, which are; i) landslides caused by the inappropriate injection and ii) contaminants increasing in the leaching solution (Xiao et al. 2015a, 2015b), which reduces the purity of rare earth products and increases precipitant consumption. To overcome this issue, the ammonium sulphate was used as a leaching agent in traditional *in-situ* leaching solutions to create a rare earth leaching solution with fewer contaminants (Moldoveanu & Papangelakis 2013; Yao, Ouyang & Rao 2005). Although *in-situ* leaching gave the low-grade of rare earth deposits (0.05-0.2%), mining and processing are simple. This is an easy technique and is possible to produce REOs with low radioactive element content (Clark & Zheng 1991; Kanazawa & Kamitani 2006).

CONCLUSION

Rare earth elements are now seen as vital components in high-tech and eco-friendly industries. This study highlights the geochemical behavior, mineral associations, and distribution patterns of REE deposits in the Western Belt of Peninsular Malaysia. The Western Belt granites, mainly S-type and peraluminous, show potential as economically viable sources of REEs, especially when weathered into clay-rich profiles that enhance ion-exchange capacity. This study also believes that the *in-situ* leaching method is the optimal approach for extraction due to its efficiency in leaching and its ability to prevent groundwater contamination. The REE occurrences in this region are primarily associated with weathered granitic rocks and ion-adsorption clay deposits, where light rare earth elements (LREEs) are more dominant in upper horizons, while heavy rare earth elements (HREEs) tend to concentrate in lower terrains and deeper weathered layers, particularly in col areas. With the right technologies and regulations in place, Malaysia stands poised to become a key player in the global REE supply chain.

ACKNOWLEDGEMENTS

The study received funding from Tenaga Nasional Berhad (TNB) and UNITEN under project code J510050002/REE2022.

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