Bulletin of the Geological Society of Malaysia, Volume 81, May 2026, pp. 5 - 19
DOI: https://doi.org/10.7186/bgsm81202602

Ion-adsorption clay-type rare earth elements in the Western Belt of Peninsular Malaysia: A study on the influence of tin-bearing S-type granites

Fakhruddin Afif Fauzi[1,*], Arda Anasha Jamil[2], Noran Nabilla Nor Azlan[3], Muhammad Azman Aseri[4], Azmi Abu Bakar[5], Iszaynuddin Abd Hamid[5], Yong Adilah Mustafa[1], Abdul Hadi Abdul Rahman[3], Mohd Zahar Ibrahim[6], Tamilarasi Ganasan[6]

[1]Department of Mineral and Geoscience Kedah/Perlis/Pulau Pinang, Jln Perak, Off Jln Putra, 05150 Alor Setar, Kedah, Malaysia
[2]Department of Mineral and Geoscience Headquarters, Level 9, PjH Tower, Precinct 2, 62000 Putrajaya, Malaysia
[3]Department of Mineral and Geoscience Negeri Sembilan/Melaka, Jln Tunku Kurshiah, 70400 Seremban, Negeri Sembilan, Malaysia
[4]Department of Mineral and Geoscience Perak, Jln Sultan Azlan Shah, 31400 Ipoh, Perak, Malaysia
[5]Department of Mineral and Geoscience Sarawak, Jln Wan Abdul Rahman, Kenyalang Park, P.O. Box 56, 93712 Kuching, Sarawak, Malaysia
[6]Department of Mineral and Geoscience Malaysia, Technical Service Division, Jln Sultan Azlan Shah, 31400 Ipoh, Perak, Malaysia
* Corresponding author email address: afif@jmg.gov.my

Abstract: The Late Triassic S-type granites in Peninsular Malaysia are known for their tin-bearing characteristics, which contribute to placer deposits in the Kinta and Klang Valleys. However, the role of these granites in the formation of ion-adsorption clay-type rare earth element (IAC-REE) deposits remains poorly understood. This study examines IAC-REE content in weathered profiles from five locations: Kampung Bandar (Kedah), Tibang (Perak), Kerling (Selangor), Kampung Purun (Negeri Sembilan), and Ladang Pagoh (Johor). The analysis was conducted using X-ray fluorescence (XRF), X-ray diffraction (XRD), and inductively coupled plasma mass spectrometry (ICP-MS) on soil and rock samples. The total rare earth element (TREE) content in the weathered profiles ranges from 222 to 677 ppm, with higher light rare earth element (TLREE) content (144–566 ppm) compared to heavy rare earth elements (THREE) (62–111 ppm). Chondrite-normalized REE plots show both enrichment and depletion relative to the granitic parent rocks. The variation in REE content is influenced by factors such as the presence of REE-bearing minerals, clay content, and profile thickness.

Keywords: REE, Malaysia, S-type, granites, IAC, economic geology

INTRODUCTION

Rare earth elements (REE) are rapidly emerging as some of the most valuable commodities, due to their unique applications and significance in advanced technology manufacturing. Many countries regard REE as strategic and critical minerals due to their relevance across various technologies (Hatch, 2012). It comprises of all 15 lanthanides: cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lanthanum (La), lutetium (Lu), neodymium (Nd), praseodymium (Pr), promethium (Pm), samarium (Sm), terbium (Tb), thulium (Tm) and ytterbium (Yb), as well as yttrium (Y) and scandium (Sc) (Connelly & Damhus, 2005).

While these elements are typically found together in the Earth's crust, the 4 elements; Nd, Pr, Tb, and Dy are particularly valuable due to their role in neodymium-iron-boron (NdFeB) permanent magnets, which are essential for electric vehicles and offshore wind turbines aligned with green energy initiatives (Project Blue, 2022; Ormerod *et al*., 2023).

REE were historically mined from REE-bearing minerals like monazite and xenotime, which are often found as byproducts of alluvial tin mining. Currently, REE extraction from mineral deposits is primarily conducted by companies like Lynas, which mines lateritic bastnaesite at Mount Weld in Australia.

Ion exchangeable REE in regolith-hosted, or ion-adsorption clay-type REE deposit (IAC-REE) were first discovered in Longnan district, South China in the early 1970's (Neary & Highley, 1984). The enrichment of REE in weathered profiles are due to metamictization of REE rich minerals such as bastnaesite and fluoroapatite.

According to Sanematsu & Watanabe (2016), the term 'ion-adsorption type' could be used if the total REE (TREE) content in a weathered profile is 50% greater than

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

in the parent rock. In comparison with other types of REE deposit, mining from the ion-adsorption type is regarded as environmentally friendly as it involves an in-situ leaching technique that produces relatively lower radioactive contamination than mining from other sources, such as in mineral form. Hence, REE sourced from ion-adsorption clays is also regarded as non-radioactive rare earth elements (NR-REE). IAC-REE is classified as one of the strategic minerals in Malaysia, in addition to bauxite, tin, silica sand and kaolin. The IAC-REE resources in Malaysia are estimated in value at RM 747.2 billion (KeTSA, 2021). According to REE exploration guideline (Basiran *et al*., 2023), TREE content above 500 ppm in weathered profiles is considered indicative of IAC-REE potential area.

The enrichment of IAC-REE in Malaysia is believed to be linked to tin-bearing granites, particularly those containing REE-bearing accessory minerals such as monazite and xenotime. These minerals are commonly found in placer tin deposits in the Kinta and Klang Valleys. However, the exact relationship between tin-bearing granites and the enrichment patterns of IAC-REE, particularly in the western belt of Peninsular Malaysia, remains insufficiently understood. This study aims to fill this gap by investigating how the characteristics of these granites influence the distribution and enrichment of IAC-REE in weathered profiles across the region.

Historical studies of REE in Malaysia

Early studies on REE in Peninsular Malaysia focused on the occurrence of the accessory minerals, from alluvial and placer deposits as part of Regional Mapping Program by the Geological Survey Department back in 1970, and later in Regional Geochemical Sampling nationwide.

The preliminary study on IAC-REE deposit in weathered granites only began in 2013, conducted by the Academy of Sciences Malaysia (ASM, 2014). In 2016, the Department of Mineral and Geoscience Malaysia (JMG) expanded on this work with a reconnaissance study of REE, thorium (Th), and scandium (Sc) in weathered igneous profiles across the country. This study found that nearly all granitic weathered profiles contained TREE concentrations exceeding 300 ppm, indicating significant potential for further investigation and targeted sampling in these areas (Basiran *et al*., 2023).

Apart from studies conducted by government agencies, research on REE related to granites and other igneous rocks has also been carried out by various researchers, including Wan Hassan & Hamzah (1999), Yaraghi *et al*. (2016, 2020), Shafiee *et al*. (2020), Baioumy *et al*. (2021), Patah *et al*. (2021), Khairulanuar *et al*. (2022), Taniou *et al*. (2022), Fauzi *et al*. (2023), Arifin *et al*. (2023a, 2023b) and Ibad *et al*. (2024).

GEOLOGICAL SETTING

The granites in Peninsular Malaysia are divided into 3 provinces, which are the Western province, the Central province and the Eastern province.

The Western Province, or Western Belt, is a segment of the Southeast Asian Magmatic Arc that was active during the Late Permian to Triassic period, following the subduction-collision event after the closure of the Paleo-Tethyan Ocean beneath the Indochina crust (Robb, 2019).

The Western Belt consists of one massive, elongated granitoid bodies, which is known as the Main Range Granite or Batholith, Bintang Batholith and several small plutons. Quek *et al.* (2015) divided the batholiths into 4 main facies; (i) biotite granite, (ii) amphibole-bearing granite, (iii) subvolcanic and volcanic±dacite and orthopyroxene rhyodacite, and (iv) microgranite and mesogranite associated with aplopegmatite.

The Main Range Granites refer to the granites found in the Western Belt, or Western Granite Province, of Peninsular Malaysia. This region stretches from Belom, Perak in the north to Batang Melaka, Melaka in the south.

Quek *et al*. (2017) noted that the Bintang Batholith stretches from the Bubu pluton in the south to the Damar and Selama areas in northern Perak. However, this paper assumed that the batholith may extend further north into Kedah, potentially encompassing granites such as Inas, Kupang, Rimba Telui, Bukit Perak, and Bukit Enggang.

The Western Belt granites are dominated by S-type granite, that is related to sedimentary protolith. According to Ghani (2005), the granites fall in monzogranite to syenogranite range, with the minerals occurring, in decreasing abundance, are K-feldspar, quartz, plagioclase, biotite, muscovite, allanite, zircon, sphene, apatite, secondary epidote, tourmaline, ilmenite, amphibole, andalusite and garnet, while monazite is the usual accessory mineral and apatite commonly exist as inclusion in biotite. Exceptions are in parts of Bintang Batholith where more mafic, amphibole-pyroxene enclaves dominate the granitoids (Quek *et al*., 2017).

The S-type granite of the Western Belt is characterized by a restricted SiO_2 content ranging from 65% to 75%. According to Chappell & White (1984, 2001), this is attributed to the sialic protolith. Additionally, these granites are low in Na and Ca, which are lost during the weathering of feldspar to clay minerals, resulting in a peraluminous characteristic. In comparison, the I-type granite has expanded the compositional range of SiO_2 from 50 to 78%, but relatively higher Na_2O than the S-type granite of the Western Belt (Ghani, 2005).

The Main Range granites in the Western Belt, and Eastern Belt are also regarded as tin bearing granites. Ishihara *et al*. (1979) classified those granites to be in ilmenite-series where divalent-state tin is mineralized as ores in late phase magmatic event. Ng *et al*. (2015) and Yeap (1993) suggested that the tin-bearing characteristics of the Main Range granites are induced by a reduction in the oxidation state of the parental sedimentary-origin magma, which leads to higher tin concentrations in the magmatic aqueous phase.

STUDY AREA

This study focused on five areas in the western belt of Peninsular Malaysia: Kampung Bandar (Kedah), Tibang (Perak), Kerling (Selangor), Kampung Purun (Negeri Sembilan), and Ladang Pagoh (Johor). Prior to 2021, these locations underwent follow-up studies conducted by JMG, which further assessed their potential for IAC-REE resources. These areas were selected because they are representative of the tin-bearing granites of the Western Belt, and they provide a diverse range of geological characteristics that are crucial for understanding the variation in IAC-REE enrichment across the region (Figure 1).

Kampung Bandar (Kedah)

This study area is situated in Baling district, Kedah. This area features an elevated hill (120 - 320 m), namely Bukit Setang, that extends from the Rimba Teloi Forest Reserve to the west and is surrounded by orchards and rubber plantations. This area is underlain by Kupang Granite, as mapped by Burton (1970). The southern area of the hill, an old alluvial tin mine that operated in the 1920s (Willbourn, 1925), had monazite as a common accessory mineral.

Tibang (Perak)

This study area is located near Slim River in the Muallim district of Perak. The hilly terrain (147 - 366 m) is predominantly covered by palm oil plantations. According to Gan (1992), the region is underlain by Main Range Granite, with accessory minerals such as monazite, xenotime, and smaller amounts of zircon commonly found in the nearby streams.

Kerling (Selangor)

This study area is located in the Hulu Selangor district of Selangor. It features a hilly landscape (160 - 560 m) that extends from the Kerling Forest Reserve in the northeast, and it remains covered with secondary forest vegetation. According to Cobbing *et al*. (1992), the geology of the area is classified as Kalumpang Granite, which is part of the Gap/Bukit Tinggi Pluton. While the pluton is largely composed of very coarse, K-feldspar megacrystic biotite granite, the Kalumpang Granite mainly exhibits micrgranite to mesogranite characteristics.

Kampung Purun (Negeri Sembilan)

Kampung Purun is located in Kuala Pilah district, Negeri Sembilan. The hilly area (80 - 240 m) is covered with rubber plantations. This area is also bedded by the southern portion of the Main Range Granite, known as Tampin Pluton. Cobbing *et al*. (1992) described the granite as coarse, K-feldspar megacrystic biotite granite with micrgranite appearing scarcely.

Ladang Pagoh (Johor)

Ladang Pagoh, situated in the Muar district of Johor, is characterized by gently to moderately undulating terrain, ranging from 20 to 140 meters in elevation. The area is predominantly cultivated with oil palm plantations. Geologically, it is underlain by porphyritic to non-porphyritic biotite granites of intermediate to coarse grain size, which are part of the Bukit Mor Granite (Kadir, 1992). Pegmatitic veins, including graphic and feldspar–muscovite varieties, are also present within the granitic body. Historically, the area hosted alluvial tin mining operations, where cassiterite—often associated with pegmatitic phases—was extracted alongside accessory minerals such as niobium–tantalum (Nb-Ta) minerals and beryl (Cobbing *et al*., 1992). Although Bukit Mor Granite is grouped under the Central Belt granites by Umor *et al*. (2011), it exhibits geochemical features characteristic of S-type granites, including peraluminous composition.

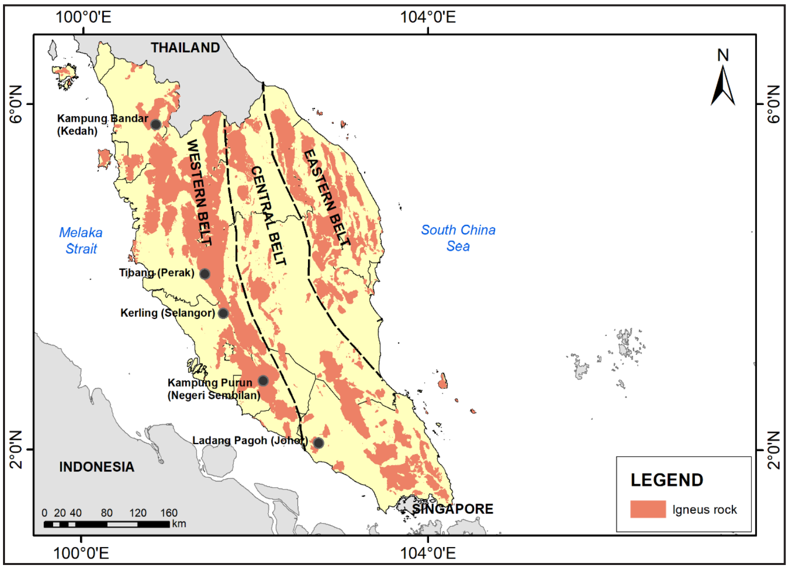

Figure 1: Map showing the granite belts in Peninsular Malaysia.

MATERIALS AND METHODS

Soil and rock sampling

In this study, soils developed on weathered granite were sampled for geochemical analysis. The samples were collected in a 1 km² grid, with a spacing of 200 meters between sampling points. Where slope cuts were unavailable, either Gannan or Edelman hand auger were used for collection (Figure 2a and 2b). Each point had at least one sample taken from a minimum depth of 3 meters below the surface, with additional samples collected at every meter down to 8 meters, where possible, encompassing the B and / or C horizons.

According to Wu *et al*. (1990), the B horizon is fully weathered bedrock, consisting of about 30% clay, 35–40% quartz, and 20–30% feldspar, and is sandy and easy to break apart by hand. In contrast, the C horizon is only partially weathered, with 15-20% clay and higher amounts of mica, feldspar, and quartz. Sanematsu *et al*. (2013) studied that the B horizon rarely retains the original texture of the granite, while the lower C horizon shows remnants of granitic textures with the rock-forming minerals such as feldspars and biotite visible to the naked eye.

Soil samples were carefully dried in the shade at room temperature prior to disaggregation. Only the fraction that passed through a 500 µm sieve was used. The purpose of sieving the soil was to eliminate quartz grains and any detrital REE-bearing minerals that could affect the geochemical results, ensuring that the contributions came solely from the ionic clays.

The sieved samples were divided into aliquots for X-Ray Fluorescence (XRF) and Loss on Ignition (LOI) analysis, as well as Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Additionally, selected soil samples underwent X-Ray Diffraction (XRD) analysis to confirm the absence of detrital REE-bearing minerals.

Fresh granitic rock samples were also collected from each study area for similar analyses.

Figure 2: a) Soil sampling of weathered profile at Kerling (Selangor) using Gannan auger. b) Soil sampling of weathered profile at Kampung Purun (Negeri Sembilan) area via Edelman auger.

Geochemical analysis

Geochemical analysis was conducted using XRF and ICP-MS instruments, which are located in the Laboratory Branch, JMG Technical Service Division.

The XRF analysis was conducted to obtain SiO_2, Al_2O_3, Fe_2O_2, TiO_2, Na_2O, K_2O, CaO, MgO, MnO, P_2O_5. The LOI was obtained using standard analytical methods. REE, Th and U contents were obtained using ICP-MS. Total light REE (TLREE), total heavy REE (THREE) and total REE (TREE) values were calculated by summing the appropriate REE values. The minimum, maximum and average values of each element, TLREE, THREE and TREE were calculated for each study area. Chondrite-normalized values were calculated using chondritic element abundances published in Sun & McDonough (1989) to produce chondrite-normalized REE plots.

X-ray diffraction (XRD) analysis

The XRD analysis of selected soil and rock samples was conducted in the Mineralogy and Petrology Laboratory, JMG Technical Service Division.

The analysis was conducted to identify clay minerals, and traces of Rare Earth-bearing minerals in the soil samples, and REE-bearing accessory minerals in the granite samples. The samples were ground to 25 microns and loaded into standard XRD powder sample holders. Diffractograms were acquired between 0 and 60 degrees 2θ. Peaks were identified using Panalytical's Xpert Highscore Plus™ software, and quantification was conducted.

RESULTS

The XRF analysis (Table 1) indicates that the SiO_2 and Al_2O_3 content in soil samples from all study areas is higher than that of other major oxides.

Among the samples, those from Ladang Pagoh show the broadest range and highest SiO_2 content (33.00 – 79.00%, average 56.00%), while the samples from Kerling has the lowest average SiO_2 content (45.00%).

Samples from Kampung Purun exhibit the highest average concentrations of Al_2O_3, measuring 31.00%. In contrast, soil samples from Kampung Bandar has the lowest average Al_2O_3 content (25.00%).

The average Fe_2O_3 content in soil samples from Kampung Purun is 5.10%. In contrast, samples from Ladang Pagoh show a wider range, with Fe_2O_3 content varying from 0.50% to 17.40%.

The K_2O content in soil samples from all study areas is generally higher than the Na_2O content. The CaO and MgO levels are very low across all samples, with the exception of Kampung Purun, where one collected sample contains up to 0.41% CaO and 0.89% MgO.

The average TiO_2 and MnO contents are relatively low across all soil samples, at no greater than 0.80% and 0.06%, respectively. Similarly, the P_2O_5 content is also low in all samples, although those from Tibang and Kampung

Table 1: Results of XRF and LOI analyses for soil samples, presented as ranges (%). The average value is indicated in parentheses.

Study Area	Kampung Bandar, Kedah	Tibang, Perak	Kerling, Selangor	Kampung Purun, Negeri Sembilan	Ladang Pagoh, Johor
SiO_2 (wt%)	40.00 - 65.00 (51.00)	36.00 - 61.00 (47.00)	38.00 - 54.00 (45.00)	35.00 - 56.00 (47.00)	33.00 - 79.00 (56.00)
Al_2O_3 (wt%)	18.00 - 30.00 (25.00)	23.00 - 39.00 (33.00)	25.00 - 35.00 (30.00)	23.00 - 38.00 (31.00)	14.00 - 38.00 (28.00)
Fe_2O_3 (wt%)	0.60 - 8.80 (4.80)	1.00 - 7.20 (3.40)	2.40 - 7.40 (4.60)	1.20 - 12.30 (5.10)	0.50 - 17.40 (2.80)
TiO_2 (wt%)	0.10 - 1.40 (0.60)	0.20 - 1.10 (0.40)	0.20 - 0.90 (0.50)	0.20 - 1.60 (0.80)	0.10 - 1.50 (0.30)
Na_2O (wt%)	0.01 - 0.73 (0.14)	0.01 - 0.65 (0.10)	0.01 - 0.19 (0.07)	0.01 - 3.88 (0.21)	0.01 - 1.04 (0.05)
K_2O (wt%)	0.35 - 7.66 (2.98)	0.05 - 8.54 (2.51)	0.13 - 7.68 (2.11)	0.04 - 6.88 (2.17)	0.02 - 3.55 (0.50)
CaO (wt%)	0.01 - 0.04 (0.01)	0.01 - 0.18 (0.02)	0.01 - 0.02 (0.01)	0.01 - 0.41 (0.02)	0.01 - 0.04 (0.01)
MgO (wt%)	0.01 - 1.14 (0.30)	0.01 - 0.06 (0.01)	0.02 - 0.13 (0.07)	0.03 - 0.89 (0.23)	0.01 - 0.19 (0.07)
MnO (wt%)	0.01 - 0.04 (0.02)	0.02 - 0.16 (0.06)	0.01 - 0.04 (0.01)	0.01 - 0.06 (0.02)	0.01 - 0.16 (0.03)
P_2O_5 (wt%)	0.01 - 0.07 (0.04)	0.02 - 0.16 (0.06)	0.01 - 0.06 (0.02)	0.01 - 0.10 (0.03)	0.01 - 0.07 (0.01)
LOI (wt%)	8.00 - 20.00 (13.00)	7.00 - 18.00 (13.00)	10.00 - 23.00 (17.00)	8.00 - 18.00 (13.00)	6.00 - 16.00 (11.00)

Purun have slightly higher levels, measuring 0.16% and 0.10%, respectively.

The LOI content (Table 1) in soil samples from all study areas ranges from 6.00% to 23.00%, with average values between 11.00% and 17.00%. The lowest values are found in samples from Ladang Pagoh.

The LA-ICP-MS results for soil (Table 2) indicate that the average TREE ranges from 196.0 to 677.0 ppm. While samples from Kampung Purun have the highest average value, the soils from Kerling reach TREE levels of up to 2,019.0 ppm. In contrast, samples from Ladang Pagoh show TREE results as low as 23.0 ppm.

In general, the average TLREE content is significantly higher than the THREE content in soil samples from all areas, except for those from Ladang Pagoh, where the maximum values of TLREE and THREE are relatively similar, that is 760.0 and 680.0 ppm, respectively.

As samples from Kampung Purun exhibit the highest average TREE content, most individual elements also display their highest concentrations from this area. Exceptions include Ce, which has the highest levels in samples from Kerling, while Eu and Yb are most concentrated in samples from Ladang Pagoh.

The XRF analyses of rock samples (Table 3) show higher SiO_2 (52.70 – 89.10%) but lower Al_2O_3 (6.36 – 19.10%) and LOI contents (0.53 – 12.50%), in comparison with soil samples of the weathered profiles.

The SiO_2 content of porphyritic biotite granite from all study areas ranges from 67.40% to 78.00% (Figure 3). In Kampung Bandar, the altered granite exhibits a significantly lower SiO_2 content of 52.70% (Figure 4), while the altered granite sampled in Kampung Purun has a much higher SiO_2 content of 89.10%.

The Na_2O and K_2O content in rock samples is significantly higher than in soil samples, with K_2O consistently exceeding Na_2O across all rock samples, excluding sample AJ/R003 of Ladang Pagoh.

The P_2O_5 content in the samples ranges from 0.01% to 0.16%. The lowest concentration is found in the altered granite from Kampung Purun, while the porphyritic biotite granite from Kampung Bandar exhibits the highest content.

The TREE content in rock samples (Table 3) ranges from 86 to 571 ppm, by which the highest originated from porphyritic biotite granite sampled near Ladang Pagoh. The lowest TREE content is from altered granite from Kampung Purun. The TREE content in all samples is contributed the most by TLREE rather than THREE.

In general, Ce (26.50 – 219.00 ppm) content has the highest content in all rock samples, followed by La (15.50 – 110.00 ppm), Nd (9.78 – 105.00 ppm) and Pr (2.70 – 29.50 ppm).

The XRD analysis of 4 soil samples from weathered profiles in Kampung Bandar and Kampung Purun revealed a predominant presence of clay minerals, specifically kaolinite,

Table 2: Results of LA-ICP-MS for soil samples, presented as ranges (ppm). The average value is indicated in parentheses.

Study Area	Kampung Bandar, Kedah	Tibang, Perak	Kerling, Selangor	Kampung Purun, Negeri Sembilan	Ladang Pagoh, Johor
Data count	40	155	33	35	80
Profile thickness (m)	5	8	6	8	8
Sc (ppm)	3.7 - 17.9 (12.6)	5.2 - 19.8 (10.6)	7.3 - 20.0 (11.3)	11.4 - 23.9 (17.4)	4.9 - 77.1 (17.8)
Y (ppm)	5.0 - 112.0 (36.0)	1.0 - 308.0 (22.0)	6.0 - 327.0 (35.0)	4.0 - 292.0 (63.0)	3.0 - 213.0 (25.0)
La (ppm)	22.0 - 186.0 (67.0)	3.0 - 299.0 (65.0)	10.0 - 579.0 (83.0)	13.0 - 680.0 (125.0)	0.0 - 63.0 (10.0)
Ce (ppm)	63.0 - 380.0 (182.0)	48.0 - 577.0 (228.0)	121.0 - 801.0 (303.0)	74.0 - 545.0 (265.0)	8.0 - 609.0 (83.0)
Pr (ppm)	4.0 - 50.0 (16.0)	1.0 - 64.0 (14.0)	3.0 - 110.0 (17.0)	3.0 - 121.0 (28.0)	0.0 - 52.0 (6.0)
Nd (ppm)	20.0 - 244.0 (75.0)	3.0 - 222.0 (41.0)	9.0 - 443.0 (56.0)	8.0 - 486.0 (109.0)	0.0 - 145.0 (15.0)
Sm (ppm)	3.0 - 40.0 (14.0)	1.0 - 31.0 (8.0)	2.0 - 75.0 (10.0)	2.0 - 74.0 (20.0)	0.0 - 2.0 (1.0)
Eu (ppm)	0.0 - 4.3 (1.5)	0.0 - 2.3 (0.5)	0.0 - 4.3 (0.5)	0.0 - 6.7 (1.9)	0.0 - 55.8 (7.8)
Gd (ppm)	3.5 - 32.5 (11.2)	0.4 - 27.9 (4.9)	1.6 - 52.5 (6.9)	0.1 - 61.8 (15.9)	1.0 - 47.4 (8.2)
Tb (ppm)	0.3 - 3.3 (1.1)	0.1 - 6.3 (0.8)	0.2 - 9.4 (1.2)	0.3 - 6.9 (2.1)	0.2 - 11.7 (1.4)
Dy (ppm)	1.6 - 21.7 (7.5)	0.4 - 40.0 (4.3)	1.1 - 54.0 (6.8)	1.3 - 43.7 (12.4)	1.1 – 61.3 (7.8)
Ho (ppm)	0.2 - 3.2 (1.2)	0.1 - 8.1 (0.8)	0.2 - 11.4 (1.4)	0.2 - 8.2 (2.4)	0.3 – 13.5 (1.8)
Er (ppm)	0.9 - 11.6 (4.2)	0.3 - 20.1 (2.2)	0.7 - 27.3 (3.8)	0.6 - 22.0 (6.7)	0.9 – 38.3 (5.0)
Tm (ppm)	0.1 - 1.4 (0.5)	0.1 - 3.2 (0.4)	0.2 - 4.9 (0.7)	0.1 - 3.4 (1.0)	0.1 – 6.0 (0.8)
Yb (ppm)	1.1 - 12.3 (4.5)	0.5 - 18.2 (2.9)	1.2 - 28.8 (4.7)	0.6 - 23.6 (6.6)	1.2 – 33.0 (5.9)
Lu (ppm)	0.1 - 1.5 (0.6)	0.1 - 2.7 (0.5)	0.2 - 4.3 (0.7)	0.1 - 3.1 (0.9)	0.1 – 4.6 (0.7)
TLREE (ppm)	157.0 - 797.0 (368.0)	75.0 - 977.0 (365.0)	169.0 - 1516.0 (481.0)	243.0 - 1551.0 (566.0)	14.0 – 643.0 (132.0)
THREE (ppm)	14.0 - 199.0 (67.0)	3.0 - 434.0 (38.0)	12.0 - 510.0 (62.0)	7.0 - 440.0 (111.0)	9.0 – 483.0 (65.0)
TREE (ppm)	185.0 - 996.0 (435.0)	79.0 - 1056.0 (403.0)	190.0 - 2019.0 (542.0)	254.0 - 1826.0 (677.0)	23.0 – 769.0 (196.0)

Figure 3: Porphyritic biotite granite with feldspar phenocryst is commonly found in Kampung Bandar (Kedah).

Figure 4: Altered (greisenized) granite with appearance of sericites found at northeastern part of Kampung Bandar (Kedah).

and dickite/sanidine/nacrite. Additionally, minor quantities of feldspars and mica (including muscovite and biotite) were identified. Notably, no RE minerals were detected in these samples.

The XRD result for soil sample KS523 (Figure 5a), which contains 906 ppm TREE, indicates the presence of kaolinite (77.1%), mica+muscovite (20.8%), albite (2.0%) and trace amount of biotite.

The XRD result for soil sample KS513C (Figure 5b), containing 644 ppm TREE, shows the occurrence of kaolinite (55.3%), dickite (37.9%), microcline (6.1%) and orthoclase (0.7%).

The XRD result for soil sample NSPR4/003 (Figure 5c), which contains 1,723 ppm TREE, indicates the presence of nacrite (38.1%), kaolinite (30.6%), orthoclase (22.6%) and biotite (8.7%).

Table 3: Results of XRF (%), LOI (%) and LA-ICP-MS (ppm) analysis for rock samples.

Sample No.	**KR501**	**KR502**	**TR3A**	**T30R**	**T35R**	**T46R**	**KHSR01**
Rock Type	Altered Granite	Porphyritic Biotite Granite	Porphyritic Biotite Granite	Porphyritic Biotite Granite	Porphyritic Biotite Granite	Porphyritic Biotite Granite	Porphyritic Biotite Granite
Study Area	Kampung Bandar, Kedah		Tibang, Perak				Kerling, Selangor
SiO_2 (wt%)	52.70	70.80	78.00	67.40	72.70	71.00	74.80
Al_2O_3 (wt%)	19.10	13.40	12.00	17.80	14.60	13.90	12.90
Fe_2O_3 (wt%)	5.93	2.63	0.76	1.04	1.15	2.05	1.94
TiO_2 (wt%)	1.05	0.47	0.16	0.15	0.16	0.27	0.26
Na_2O (wt%)	0.21	1.55	0.28	0.52	3.20	3.28	3.04
K_2O (wt%)	5.53	4.69	7.22	9.12	6.45	4.88	4.83
CaO (wt%)	0.08	0.72	0.37	0.14	0.46	2.04	1.21
MgO (wt%)	0.65	1.42	0.31	0.20	0.21	0.89	0.24
MnO (wt%)	0.03	0.05	0.02	0.02	0.02	0.04	0.04
P_2O_5 (wt%)	0.08	0.16	0.11	0.07	0.14	0.08	0.06
LOI (wt%)	12.50	3.90	1.24	3.16	1.08	1.77	0.53
Sc (ppm)	10.20	8.29	2.45	4.41	4.84	5.20	5.47
Y (ppm)	11.90	36.00	18.00	35.50	45.40	47.70	39.90
La (ppm)	22.10	56.70	16.20	62.30	58.70	25.60	92.30
Ce (ppm)	77.80	113.00	30.00	98.70	122.00	50.50	204.00
Pr (ppm)	5.90	13.40	2.70	14.40	13.40	5.42	29.50
Nd (ppm)	26.70	56.30	9.78	51.10	45.90	21.00	61.70
Sm (ppm)	4.94	11.10	1.22	10.00	8.70	4.17	14.60
Eu (ppm)	0.46	1.31	0.15	0.61	0.42	0.57	1.13
Gd (ppm)	3.83	8.03	1.94	7.80	7.09	4.23	10.80
Tb (ppm)	0.38	1.30	0.44	1.44	1.36	0.93	1.87
Dy (ppm)	2.50	8.36	2.77	7.54	7.92	6.49	11.00
Ho (ppm)	0.36	1.52	0.57	1.35	1.54	1.53	2.34
Er (ppm)	1.38	4.47	1.57	3.37	4.12	4.57	5.97
Tm (ppm)	0.17	0.66	0.17	0.45	0.57	0.77	0.88
Yb (ppm)	1.63	3.42	1.86	3.52	4.32	6.31	5.96
Lu (ppm)	0.22	0.48	0.21	0.44	0.54	0.92	0.84
TREE (ppm)	170.00	324.00	90.00	303.00	327.00	186.00	488.00
TLREE (ppm)	148.00	260.00	63.00	242.00	254.00	112.00	409.00
THREE (ppm)	22.00	64.00	28.00	61.00	73.00	73.00	80.00
Th (ppm)	46.30	46.60	27.20	50.10	58.90	55.10	217.00
U (ppm)	6.31	22.70	16.10	21.40	33.50	25.90	30.20

The XRD result for soil sample NSPR21/008 (Figure 5d), containing 1,826 ppm TREE, reveals the presence of kaolinite (40.0%), sanidine (40.6%), nacrite (10.4%), monalbite (8.8%), and trace amounts of montmorillonite.

The chondrite-normalized plots of all samples from the study areas reveal a general downward trend from La to Lu with notable negative Eu anomaly, indicating a consistent pattern across the samples. The negative Eu

Table 3: Continued.

Sample No.	NSPR 19/R001	NSPR 22/R001	NSPR 31/R001	NSPR 17/R001	NSPR 12/R001	AJ/ R003	4153/ R012
Rock Type	Altered Granite	Porphyritic Biotite Granite	Porphritic Biotite Granite	Porphyritic Biotite Granite	Porphyritic Biotite Granite	Porphritic Biotite Granite	Porphyritic Biotite Granite
Study Area	Kampung Purun, Negeri Sembilan					Ladang Pagoh, Johor	
SiO_2 (wt%)	89.10	73.20	70.80	73.50	72.50	70.20	68.20
Al_2O_3 (wt%)	6.36	13.90	13.50	13.50	13.80	16.50	14.80
Fe_2O_3 (wt%)	0.44	1.61	3.31	1.66	2.25	1.52	2.93
TiO_2 (wt%)	0.17	0.28	0.61	0.32	0.40	0.07	2.93
Na_2O (wt%)	0.02	2.78	1.99	1.86	2.52	5.29	4.04
K_2O (wt%)	2.04	5.73	4.86	6.06	5.60	4.94	5.50
CaO (wt%)	0.02	1.27	1.34	0.65	1.56	0.26	1.26
MgO (wt%)	0.33	0.55	1.38	0.60	0.86	0.02	0.56
MnO (wt%)	0.01	0.04	0.05	0.03	0.04	0.03	0.09
P_2O_5 (wt%)	0.01	0.07	0.14	0.04	0.10	0.02	0.10
LOI (wt%)	1.19	0.84	2.14	2.04	0.60	1.33	0.86
Sc (ppm)	4.87	8.00	10.70	7.62	8.84	-	-
Y (ppm)	10.90	55.00	32.60	20.50	28.30	40.00	45.60
La (ppm)	15.50	37.70	51.50	34.00	33.60	60.60	110.00
Ce (ppm)	26.50	83.80	101.00	111.00	82.60	115.00	219.00
Pr (ppm)	3.74	10.30	13.30	7.79	8.16	16.50	29.00
Nd (ppm)	16.00	40.50	51.60	30.20	30.00	67.00	105.00
Sm (ppm)	2.87	8.81	9.93	5.92	6.18	14.50	25.70
Eu (ppm)	0.29	0.61	1.17	0.66	0.66	1.18	2.10
Gd (ppm)	0.05	4.86	5.19	1.76	2.23	12.50	10.00
Tb (ppm)	0.38	1.44	1.25	0.77	0.83	1.38	1.76
Dy (ppm)	2.22	9.34	7.22	4.69	5.16	8.18	10.60
Ho (ppm)	0.44	1.95	1.41	0.93	1.09	1.65	1.62
Er (ppm)	1.18	5.63	3.74	2.62	3.21	4.19	2.79
Tm (ppm)	0.18	0.93	0.55	0.43	0.54	0.47	1.03
Yb (ppm)	1.09	6.16	3.46	2.89	3.67	2.86	5.54
Lu (ppm)	0.15	0.91	0.49	0.41	0.58	0.50	0.88
TREE (ppm)	86.00	276.00	295.00	232.00	216.00	347.00*	571.00*
TLREE (ppm)	70.00	189.00	239.00	197.00	170.00	275.00*	491.00*
THREE (ppm)	17.00	86.00	56.00	35.00	46.00	72.00	80.00
Th (ppm)	13.70	33.20	40.80	36.00	46.90	-	-
U (ppm)	2.67	17.50	10.90	14.40	14.80	-	-

"-" not tested, *excluding Sc

anomaly observed in the Kampung Bandar samples is less pronounced than that in samples from other areas (Figure 6a). The Ce anomaly of all areas shows either positive or negative deviation.

In comparison to the chondrite plot of rock samples, nearly all soil samples of Kampung Bandar are positioned above the porphyritic rock sample of similar pattern, suggesting an enrichment of REE in the weathered profiles (Figure 6a).

The chondrite-normalized plot for rock samples in the Tibang area (Figure 6b) reveals distinct patterns compared to the soil samples, specifically lacking both positive and negative anomalies for Ce and Eu, while showing a sudden

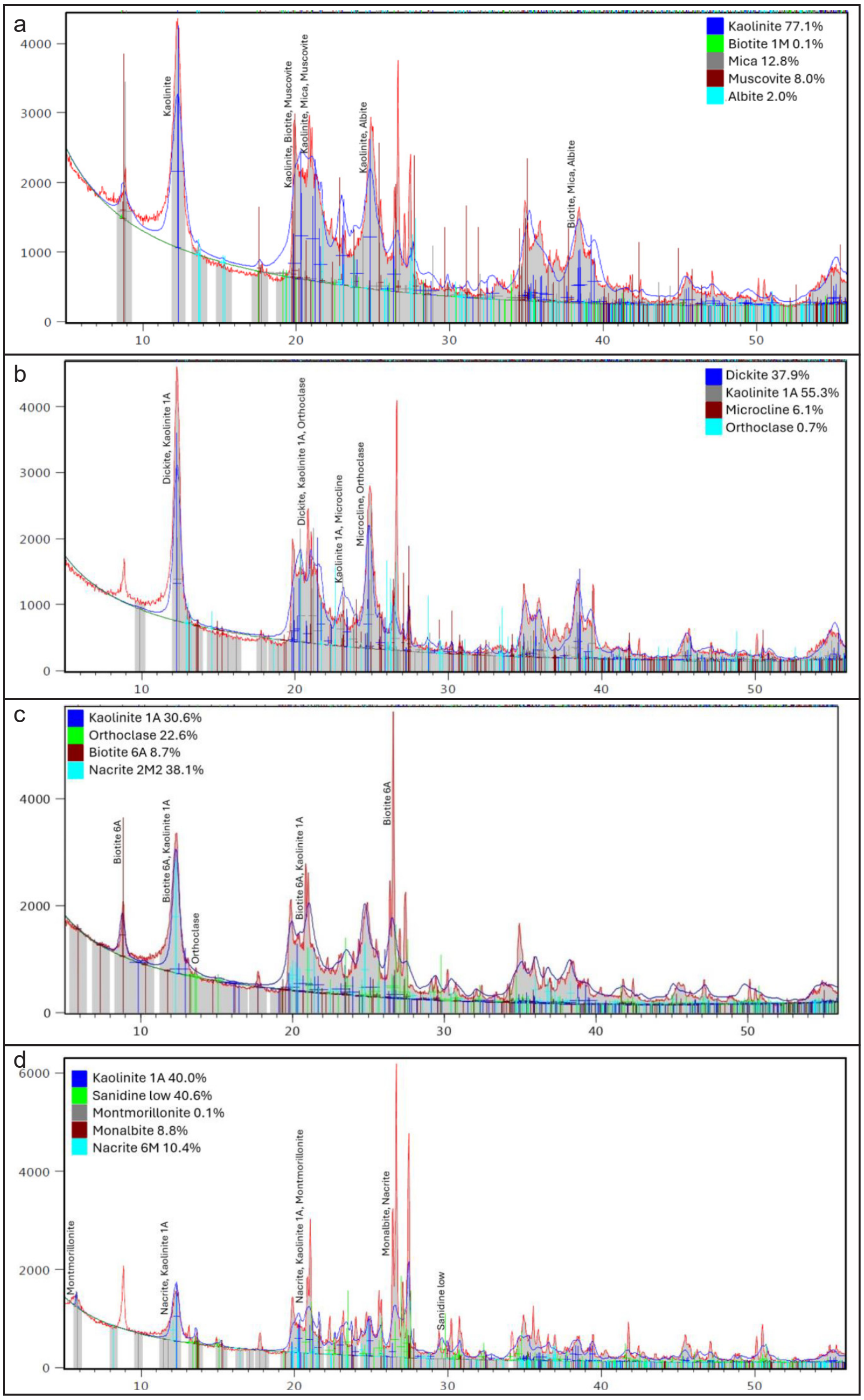

Figure 5: a) XRD diffractogram of soil sample KS523, which has TREE content of 906 ppm. b) XRD diffractogram of soil sample KS513C, which has TREE content of 644 ppm. c) XRD diffractogram of soil sample NSPR4/003, which has TREE content of 1,723 ppm. d) XRD diffractogram of soil sample NSPR21/008, which has TREE content of 1,826 ppm.

positive Tb anomaly. While nearly all the soil samples show a positive Ce anomaly, their plot patterns are the broadest compared to other areas but positioned both above and below the rock plots. This could suggest a complex process of REE enrichment and depletion.

Nearly all soil samples from Kerling exhibit a positive Ce anomaly in the chondrite-normalized plot (Figure 6c). Additionally, most of the soil samples are situated below the rock sample plot, which may suggest a greater depletion of REE rather than enrichment.

The chondrite-normalized plot for samples from Kampung Purun (Figure 6d) displays a wide range of values, with distinct positive or negative Ce anomalies. In contrast, some soil and rock sample plots exhibit negative Gd anomalies. Similar to the Tibang area, the plots from Kampung Purun are the most varied compared to other areas, appearing both above and below the rock plots.

The chondrite-normalized plot for samples from Ladang Pagoh (Figure 6e) shows little uniformity between rock and soil samples, with the exceptions of positive Ce values, a

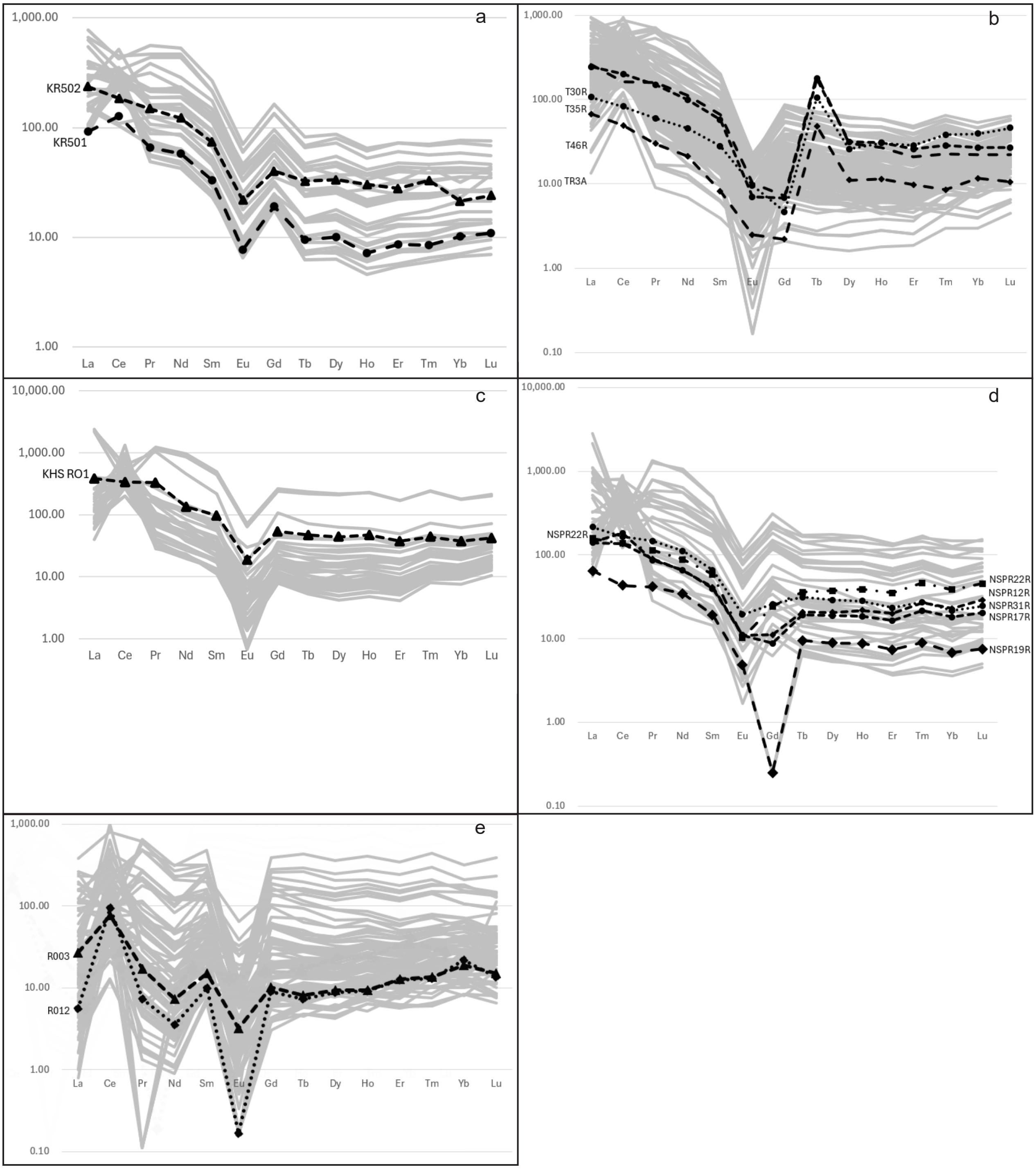

Figure 6: a) Chondrite-normalized REE patterns for rock samples (represented by black lines) in comparison with those of soil samples (grey lines) from Kampung Bandar, Kedah. b) Chondrite-normalized REE patterns for rock samples (represented by black lines) in comparison with those of soil samples (grey lines) from Tibang, Perak. c) Chondrite-normalized REE patterns for rock samples (represented by black lines) in comparison with those of soil samples (grey lines) from Kerling, Selangor. d) Chondrite-normalized REE patterns for rock samples (represented by black lines) in comparison with those of soil samples (grey lines) from Kampung Purun, Negeri Sembilan. e) Chondrite-normalized REE patterns for rock samples (represented by black lines) in comparison with those of soil samples (grey lines) from Ladang Pagoh, Johor.

downward trend from Pr to Nd, and a slight similarity in the pattern from Gd to Lu.

DISCUSSION

The occurrence of clay minerals

Higher levels of Al_2O_3 and LOI, along with lower concentrations of Na_2O and K_2O in soil compared to rock, suggest significant weathering processes. This indicates that K-feldspars or Na-rich feldspars have been transformed into clay minerals, particularly kaolinites, as detected in soils via XRD analysis:

$$\underset{\text{(K-feldspar)}}{3KAlSi_3O_8} + 2H^+ + 9H_2O \rightarrow \underset{\text{(Kaolinite)}}{Al_2Si_2O_5(OH)_4} + 3K^+ + 4H_4SiO_4$$

$$\underset{\text{(Na-rich feldspar)}}{NaAlSi_3O_8} + 2H^+ + 9H_2O \rightarrow \underset{\text{(Kaolinite)}}{Al_2Si_2O_5(OH)_4} + Na^+ + 4H_4SiO_4$$

The results align with findings by Wu *et al*. (1990), which indicate a positive correlation between Al_2O_3 and LOI as a result of progressive weathering from bedrock to weathered zones.

Higher K_2O content compared to Na_2O in rock samples is also observed in soil samples, indicating that the soil is derived from K-rich feldspars present in the rocks.

In addition to feldspars, biotite is another mineral that can naturally weather to clay minerals, including kaolinite (Fordham, 1990). While biotite is common in all rock samples, it does not appear in the soil samples, as indicated by the XRD results.

According to Li & Zhou (2020), the high kaolinite content in the lower pedolith/B horizon of the weathered profiles is considered indicative of an IAC-REE deposit. The clay minerals possess a large specific surface area (SSA) and high porosity due to their small, poorly crystalline structures, which significantly enhance their capacity for REE adsorption. Kosmulski (2018) proposed that the zeta potential of clay minerals, specifically kaolinite, reaches neutrality at a pH of approximately 3.7, which enhances its ability to readily adsorb ionic REE.

REE enrichment in weathered profiles

The elevated concentrations of REE in the weathered profiles, as indicated by soil sample analyses, suggest an IAC-type origin. Prior to laboratory analysis, the soil samples were subjected to sieving to eliminate any REE-bearing minerals. This was further validated by XRD analysis, which revealed no REE-bearing minerals detected.

The enrichment of REE in weathered profiles compared to bedrock is evident, as demonstrated by the higher TREE content in soil samples (222 – 677 ppm) than in rock samples (86 – 571 ppm).

The REE chondrite-normalized diagram was originally developed to assess the enrichment or depletion of elements in crustal rocks relative to chondritic meteorites, which are considered representative of the elemental concentrations in the universe (Schmitt *et al*., 1963, 1964). In this study, the chondrite-normalized diagram of soil and rock samples is utilized to assess the mineralization REE from bedrocks into weathered profiles.

The consistent negative Eu anomaly observed in all soil and rock samples, indicates a hereditary relationship with the parent rock. Aubert *et al*. (2000) and Compton *et al*. (2003) stated Eu can partition into plagioclase, substituting for Sr^{2+}, which can lead to positive Eu anomalies in feldspar during rock formation. However, the removal of feldspar through fractional crystallization during the fractionation of parent magmas results in negative Eu anomalies in granites, as demonstrated in studies conducted in Hong Kong (Duzgoren-Aydin & Aydin, 2009).

The chondrite-normalized REE patterns of the rock and weathered profiles demonstrate significant similarities in Kampung Bandar and Kerling, likely due to the extensive weathering of a homogeneous parent granitic rock in the area. In contrast, no similarities are observed in Tibang, Kampung Purun, and Ladang Pagoh. This discrepancy may result from the diverse bedrock types with varying compositions in these regions, as well as influences from hydrothermal processes and other factors such as groundwater table variations and soil movement, including landslides, hillslope transport and colluvial formation.

The effects of groundwater on REE content in weathered profiles varied with depth throughout the weathering process, as geological structural changes during late-stage development disrupted the earlier formation of the groundwater table. Huang *et al*. (2021) discovered that the shift from a positive to a negative Ce anomaly in chondrite-normalized REE patterns indicates changes in the groundwater table throughout the development of weathering profiles.

Li *et al*. (2020) investigated that the occurrence of hillslope erosion can be detected by abrupt changes in mineral and REE content, as well as pH values within the weathering profiles.

REE source in weathered profiles for all area

Monazite, xenotime, and zircon are common accessory minerals found in alluvial and placer tin deposits in Peninsular Malaysia, originating from tin-bearing S-type granite (Willbourn, 1925; Ibad *et al*., 2024).

Monazite is a phosphate mineral containing Ce, La, Nd, Th, and U. In peraluminous granites, monazite serves as a significant host for LREE-Eu, Th and U, with minor amounts of Y and HREE (Hinton & Paterson, 1994; Bea *et al*., 1994; Bea, 1996). According to Che Zainol Bahri *et al*. (2018), the thorium content in Malaysian monazite ranges from 2,525 ppm to 40,868 ppm, while Willbourn (1925) reported that the mineral contains 3.5% to 8.38% ThO_2.

Xenotime is another phosphate mineral that is particularly abundant in calcium-poor peraluminous granites, contributing significantly to the contents of Y and HREE, along with variable amounts of substituted U (Wark & Miller, 1993; Bea, 1996). In xenotime-bearing peraluminous granites, the fractions of Y and HREE contained in xenotime range from 30% to 50%, which is closely associated with the coexistence of xenotime, apatite, and zircon during plutonic facies differentiation (Wark & Miller, 1993; Förster & Tischendorf, 1994; Bea, 1996). Additionally, xenotime contains minor amounts of Th and LREE, particularly Nd and Sm (Förster, 1998).

Zircon is the most common refractory mineral found in alluvial tin deposits and is primarily composed of zirconium silicate. Radioactive elements such as Th and U are present as inclusions within the zircon structure. The Y content in zircon ranges from 1,100 to 23,900 ppm, while the average REE content is approximately 4,200 ppm (Levashova *et al*., 2024).

Several studies suggest that these minerals may be a significant source of REE in weathered granite profiles, attributed to the metamictization process. This process involves the destruction of mineral texture in radioactive-containing minerals, transitioning them from fully crystalline to completely metamictized forms (Meldrum *et al*., 1998). This could include the refractory minerals above as all of them contain U. The weathered profiles of Zhaibei granites are enriched in REE by monazites, along with biotites, fergusonites and aeschynite (Borst *et al*., 2020). Ram *et al*. (2019) and Borst *et al*. (2020) studied the abundance of zircon in Madagascar pegmatites and peralkaline rocks, noting that it contributes to the elevated zirconium (Zr) levels in weathering profiles, which are well-correlated with the content of HREE.

Despite their generally high REE content, these minerals are unlikely to be the primary source of REE throughout the weathering process of Malaysian granitoids due to their refractory properties and resistance to weathering (Sengupta & Van Gosen, 2016; Zhou *et al*., 2017).

Apatite, along with silicate minerals such as allanite and titanite (sphene), is a more likely source of REE in the soil due to its higher solubility (Bao & Zhao, 2008; Ishihara *et al*., 2008). Fluorocarbonate minerals can crystallize in cavities and along boundaries or fractures in feldspars, as observed in the Phuket Granite (Sanematsu *et al*., 2013). Additionally, minerals such as allanite, parasite, bastnaesite, and monazite are found as inclusions within biotite and/or plagioclase in the Bangka Islands (Tampubolon *et al*., 2022).

Allanite, previously referred to as orthite, is an epidote-group mineral that has a general formula of $A_2M_3Si_3O_{12}$, where site A accommodates elements including REE, Th and U, while site M is occupied by Al, Mn, Mg, Ti, Cr and V (Xiao & Zhang, 2024). This mineral contains LREE more than 90% relative to HREE, with TREE falling within 14% to 33% (Gieré & Sorensen, 2004). Recent studies of granites in South China have confirmed that allanite serves as a significant source REE during the weathering process of the granite bodies (Zhao *et al*., 2023; Dou *et al*., 2024).

REE potential

The IAC-REE study results indicate that concentrations of rare earth elements exceeding 500 ppm are generally absent across all study areas within the S-type granitic belt in Peninsular Malaysia when considering the average TREE content per area. However, it is important to also consider other factors such as the contents of THREE and TLREE, as well as key elements like Nd, Pr, Tb, and Dy, to fully assess the potential of IAC-REE.

In addition to presenting TREE potential as elemental contents, it is advisable to express these values as TREO using conversion factors, as this aligns with the final stages of REE processing and current market pricing (Joint Ore Reserves Committee, 2012). In comparison, the Zudong deposit in Longnan has an average grade of approximately 0.1 wt.% REO (Li *et al*., 2019), equivalent to roughly 840–920 ppm TREE depending on oxide-to-element conversion. The ore zone is mainly hosted within the lower B to upper C horizons, where HREE enrichment is most pronounced (Li *et al*., 2019). Individual REE abundances reported for Zudong include relatively elevated Dy and lower Pr and Tb contents, consistent with its HREE-enriched character (Xie *et al*., 2016).

Excluding less significant elements when estimating resource potential in a given area is also practiced, as demonstrated in the Makuutu Maiden Project, where TREO is calculated by subtracting Ce_2O_3 (Ionic Rare Earths, 2022).

CONCLUSION AND RECOMMENDATIONS

The average TREE content in weathered profiles across four selected areas of S-type granites in Peninsular Malaysia ranges from 222 to 677 ppm, with Kampung Purun (Negeri Sembilan) exhibiting the highest average value and Ladang Pagoh (Johor) showing the lowest. In all study areas, the REE content is predominantly composed of LREE, with HREE contributing less to the overall concentrations.

The TREE content in rock samples ranges from 86 to 571 ppm, with the highest concentration found in porphyritic biotite granite from Ladang Pagoh (Johor). In contrast, the rock sample from Kampung Purun (Negeri Sembilan) exhibited the lowest REE content.

The higher Al_2O_3 and LOI values in soil indicate that weathering processes involving the conversion of K-feldspar and plagioclase to clay minerals, particularly kaolinite, occurred under the influence of an oxidizing environment. This is further supported by the presence of slightly negative Eu anomalies.

The elevated REE values in soil samples compared to rock samples, along with the higher levels of Al_2O_3 and LOI in the soil samples, the high proportion of clay minerals, and the absence of REE-bearing minerals, suggest that the weathered profiles in the studied granite areas can be classified as ion-adsorption clay-type deposits.

The differences in chondrite-normalized REE plots between soil and rock samples suggest either continuous weathering from a homogeneous parent rock or influences from non-homogeneous parent rocks, late-stage hydrothermal processes, or hillslope erosion. These factors may affect REE mineralization but do not necessarily impact REE potential.

The IAC-REE potential in the weathered profiles of all studied area varies and is not solely dependent on REE concentrations exceeding 500 ppm. Furthermore, the thickness of the weathered profiles may significantly influence REE potential, contributing to the calculation of resource value.

Further investigations to identify the actual source minerals for REE and to study clay mineral behavior are recommended, utilizing advanced techniques such as Electron Probe Micro-Analysis (EPMA), Field Emission Scanning Electron Microscopy (FESEM), and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS).

Additionally, assessing the REE potential in I-type granites in Peninsular Malaysia and comparing it to S-type granites is essential for effectively targeting potential IAC-REE deposits in Malaysia.

ACKNOWLEDGEMENT

The authors would like to thank the Director General of the Department of Mineral and Geoscience Malaysia (JMG) for granting permission to publish this study. The authors also wish to acknowledge the JMG REE Working Group for their valuable ideas, technical support, and contributions throughout this study. Special thanks are extended to the peer reviewers for their constructive comments and insightful suggestions, which greatly improved the quality of this manuscript.

AUTHORS CONTRIBUTION

FAF, NNNA, MAA, AAB and YAM performed field mapping and sampling. MZI and TG performed laboratory analysis and interpretations. FAF, AAJ and IAH conducted geochemical result interpretation and wrote the whole manuscript. AHAR contributed to critically reviewing the manuscript and contributing ideas to improve the paper.

CONFLICT OF INTEREST

The authors declare there is no conflict of interest.

REFERENCES

Arifin, M.H., Fauzi, F.A., Ibrahim, M.Z., Abas, M.F., Sibon, M.H., Sia, S.G., Ismail, K.I., Abdul Rahman, A.H. & Ali, A., 2023b. Geochemical and Geophysical Study on Ion Adsorption Clay Type REE Deposit in Malaysia: A Case Study in Kampung Bandar, Kedah. International Conference of Geophysics (ICOG) 2023, Penang, Malaysia.

Arifin, M.H., Jamil, A.A., Ibrahim, M.Z., Sia, S.G., Sibon, M., Salehudin, Z.F. & Sulaiman, M.A.A., 2023a. Geophysical and geochemical studies of weathered crust from granitic rocks in Bukit Pengkalan area, Muar, Johor. EAGE Conference on the Future of Energy – Role of Geoscience in the Energy Transition. https://doi.org/10.3997/2214-4609.202372039.

ASM, 2014. Blueprint for the establishment of rare earth-based industries in Malaysia: summary for policy maker. Akademi Sains Malaysia, Kuala Lumpur, Malaysia. 220 p.

Aubert, D., Stille, P. & Probst, A., 2000. REE fractionation during granite weathering and removal by waters and suspended loads: Sr and Nd isotopic evidence. Geochemica et Cosmochimica Acta, 65, 387-406.

Baioumy, H. Farahat, M., Arifin, M.H., Anuar, M.N.A. & Al-Kahtany, K., 2021. Hypogene kaolin deposits from felsic intrusive rocks (Peninsular Malaysia) with special reference to rare earth elements and stable isotopes geochemistry. Geosciences Journal, 25, 863-876. https://doi.org/10.1007/s12303-021-0003-9.

Bao, Z., & Zhao, Z., 2008. Geochemistry of mineralization with exchangeable REY in the weathering crusts of granitic rocks in South China. Ore Geology Reviews, 33, 519-535.

Basiran, Y., Abdul Rahman, A.H., Ismail, M.S., Ariffin, H., Sia, S.G., Sibon, M., Jinap, J.J., Yaakub, K.N., Zolkefli, A.I. & Fauzi, F.A., 2023. Guidelines for rare earth elements exploration (JMG.GP.20) (Second Edition) (in Malay). Department of Mineral and Geoscience Malaysia.

Bea, F., 1996. Residence of REE, Y, Th and U in granites and crustal protoliths; Implications for the chemistry of crustal melts. Journal of Petrology, 37(3), 521–552. https://doi.org/10.1093/petrology/37.6.1601.

Bea, F., Pereira, M.D., Corretge, L.G. & Fershtater, G.B., 1994. Differentiation of strongly peraluminous, perphosphorous granites: The Pedrobernardo pluton, central Spain. Geochimica et Cosmochimica Acta, 58(12), 2609–2627. https://doi.org/10.1016/0016-7037(94)90132-5.

Borst, A.M., Smith, M.P., Finch, A.A., Estrade, G., Vilanova-de-Benavent, C., Nason, P., Marquis, E., Horsburgh, N.J., Goodenough, K.M., Xu, C., Kynicky, J. & Geraki, K., 2020. Adsorption of rare earth elements in regolith-hosted clay deposits. Nature Communications, 11, 4386. https://doi.org/10.1038/s41467-020-17801-5.

Burton, C.K., 1970. The geology and mineral resources of the Baling area, Kedah and Perak. Geological Survey Headquarters, Ipoh. 150 p.

Chappell, B.W. & White, A.J.R., 1984. I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. In: Xu Keqin & Tu Guangchi (Eds.), Geology of granites and their matallogenic relation. Science Press, Beijing. 954 p.

Chappell, B.W. & White, A.J.R., 2001. Two contrasting granite types: 25 years later. Australian Journal of Earth Science, 48(4), 489–499. https://doi.org/10.1046/j.1440-0952.2001.00882.x.

Che Zainol Bahri, C.N.A., Ismail, A.F., Ab Majid, A., Mohd Ruf, M.I.F. & Al-Areqi, W.M., 2018. Extraction and purification of thorium oxide from monazite mineral. Sains Malaysiana, 47(8), 1873-1882. https://doi.org/10.17576/jsm-2018-4708-28.

Cobbing, E.J., Pitfield, P.E.J., Darbyshire, D.P.F. & Mallick, D.I.J., 1992. The granites of the South-East Asian Tin Belt. Overseas Memoir 10. B.G.S. H.M. Stationery Office, Malaysia. 369 p. ISBN 0118843869, 9780118843867.

Compton, J.S., White, R.A. & Smith, M., 2003. Rare earth element behavior in soils and salt pan sediments of a semi-arid granitic terrain in the Western Cape, South Africa. Chem. Geol., 201, 239-255.

Connelly, N.G. & Damhus, T., 2005. Nomenclature of inorganic chemistry: IUPAC recommendations. RSC Publishing, London, England. 51 p.

Dou, J., Wang, C.Y., Tan, W. & Zhao, Z., 2024. Mobilization of rare earth elements during allanite-fluid interaction: Insights into formation of regolith-hosted rare earth element deposits in South China. Miner. Deposita, 59, 1661-1678. https://doi.org/10.1007/s00126-024-01290-3.

Duzgoren-Aydin, N.S. & Aydin, A., 2009. Distribution of rare earth elements and oxyhydroxide phases within a weathered felsic igneous profile in Hong Kong. Journal of Asian Earth Sciences, 34, 1-9.

Fauzi, F.A., James, E., Musa, M.S., Ariffin, H., Sulaiman, A., Sibon, M., Abdul Rahman, A.H., Zahri, M.F. & Ali, A., 2023. Ion adsorption-type rare earth element deposits in western Peninsular Malaysia: A case study in Bukit Enggang Granite, Kedah. Bulletin of the Geological Society of Malaysia, 76, 27-45. https://doi.org/10.7186/bgsm76202303.

Fordham, A.W., 1990. Weathering of biotite into dioctahedral clay minerals. Clay minerals, 25, 51-63. https://doi.org/10.1180/claymin.1990.025.1.06.

Förster, H-J., 1998. The chemical composition of REE-Y-Th-U-rich accessory minerals in peraluminous granites of the Erzgebirge-Fichtelgebirge region, Germany. Part II: Xenotime. American Mineralogist, 83, 1302–1315.

Förster, H. & Tischendorf, G., 1994. The western Erzgebirge-Vogtland granites: implications to the Hercynian magmatism in the Erzgebirge-Fichtelgebirge anticlinorium. In: R. Seltmann, H. Kampf, & P. Moller (Eds.), Metallogeny of collisional orogens. Czech Geological Survey, Prague, Czech Republic. 448 p.

Gan, A.S., 1992. Geology and mineral resources of the Tanjung Malim area, Perak Darul Ridzuan. Geological Survey of Malaysia. Jabatan Percetakan Negara, Ipoh. 65 p.

Ghani, A.A., 2005. Geochemical characteristics of S- and I-Type Granites: Example from Peninsular Malaysia granites. Bulletin of the Geological Society of Malaysia, 51, 123-134. https://doi.org/10.7186/bgsm51200515.

Gieré, R. & Sorensen, S.S., 2004. Allanite and other REE-rich epidote group minerals. Reviews in Mineralogy & Geochemistry, 56, 431-493. https://doi.org/10.2138/gsrmg.56.1.431.

Hatch, G.P., 2012. Dynamics in the global market for rare earths. Elements, 8, 341-346.

Hinton, R.W. & Paterson, B.A., 1994. Crystallisation history of granitic magma: Evidence from trace element zoning. Mineralogical Magazine, 58A, 416-417.

Huang, J., He, H., Tan, W., Liang, Z., Ma, L., Wang, Y., Qin, X. & Zhu, J., 2021. Groundwater controls REE mineralisation in the regolith of South China. Chemical Geology, 577, 20295. https://doi.org/10.1016/j.chemgeo.2021.120295.

Ibad, S.M., Tsegab, H., Siddiqui, N.M., Adam, M., Mishra, S., Ridha, S., Ahmed, N. & Azmi, A., 2024. The upstream rare earth resources of Malaysia: Insight into geology, geochemistry, and hydrometallurgical approaches. Geoscience Frontiers, 15, 101899. https://doi.org/10.1016/j.gsf.2024.101899.

Ishihara, S., Sawata, H., Arpornsuwan, S., Busaracome, P. & Bungbrakearti, N., 1979. The magnetite-series and ilmenite-series granitoids and their bearing on tin mineralization, particularly of the Malay Peninsula region. Bulletin of the Geological Society of Malaysia, 11, 103-110. https://doi.org/10.7186/bgsm11197904.

Ishihara, S., Renmin, H., Hoshino, M. & Murakami, H., 2008. REE abundance and REE minerals in granitic rocks in the Nanling Range, Jiangxi Province, Southern China, and generation of the REE-rich weathered crust deposits. Resource Geol., 58, 355-372.

Ionic Rare Earths, 2022. Substantial increase to Makuutu REE resource to over 500 million tonnes. ASX Release 3 May 2022. Ionic Rare Earths Limited.

Joint Ore Reserves Committee, 2012. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. AusIMM Publications, Australia. 44 p. Available from: http://www.jorc.org.

Kadir, A.A., 1992. Four isolated granitoid plutons in Johor: an overview on their petrochemistry and genesis. Bulletin of the Geological Society of Malaysia, 31, 85-106.

KeTSA, 2021. National Mineral Industry Transformation Framework Plan 2021-2030. Ministry of Energy and Natural Resources, Putrajaya, Malaysia (in Malay). 48 p.

Khairulanuar, K.A., Segeran, L., Jabit, N., Ismail, S., Ibrahim, I. & Ariffin, K.S., 2022. Characterisation of rare earth elements from Malaysian ion-adsorption clay. Materials Today: Proceedings, 66, 3049-3052. https://doi.org/10.1016/j.matpr.2022.07.336.

Kosmulski, M., 2018. The pH dependent surface charging and points of zero charge. VII. Update. Advanced in Colloid and Interface Science, 251, 115-138. https://doi.org/10.1016/j.cis.2017.10.005.

Levashova, E.V., Skublov, S.G., Zamyatin, D.A., Li, Q., Levashov, D.S. & Li, X., 2024. Tetrad effect of rare earth element fractionation in zircon from the pegmatite of the Adui Massif, Middle Urals. Geosciences, 14, 7. https://doi.org/10.3390/geosciences14010007.

Li, M.Y.H. & Zhou, M., 2020. The role of clay minerals in forming the regolith-hosted heavy rare earth element deposits. American Mineralogist, 105, 92-108. https://doi.org/10.2138/am-2020-7061.

Li, M.Y.H., Zhou, M. & Williams-Jones, A.E., 2019. The genesis of regolith-hosted heavy rare earth element deposits: Insights from the World-Class Zudong Deposit in Jiangxi Province, South China. Economic Geology, 114, 543-568. https://doi.org/10.5382/econgeo.4642.

Li, M.Y.H., Zhou, M. & Williams-Jones, A.E., 2020. Controls on the dynamics of rare earth elements during subtropical hillslope processes and formation of regolith-hosted deposits. Economic Geology, 115, 1097-1118. https://doi.org/10.5382/econgeo.4727.

Meldrum, A., Boatner, L.A., Weber, W.J. & Ewing, R.C., 1998. Radiation damage in zircon and monazite. Geochimica et Cosmochimica Acta, 62, 2509-2520. https://doi.org/10.1016/S0016-7037(98)00174-4.

Neary, C.R. & Highley, D.E., 1984. The economic importance of the rare earth elements. In: Henderson, P. (Ed.), Rare earth element geochemistry. Elsevier, Amsterdam, Netherlands. 510 p.

Ng, S.W.P., Chung, S.L., Robb, L.J., Searle, M.P., Ghani, A.A., Whitehouse, M.J., Oliver, G.J.H., Sone, M., Gardiner, N.J. & Roslee, M.H., 2015. Petrogenesis of Malaysian granitoids in the Southeast Asian Tin Belt: Part 1. Geochemical and Sr-Nd isotopic characteristics. Geological Society of America Bulletin, 127, 1209-1237. https://doi.org/10.1130/B31213.1.

Ormerod, J., Karati, A., Baghei, A.P.S., Prodius, D. & Niebedim, I.C., 2023. Sourcing, refining and recycling of rare-earth magnets. Sustainability, 15(20), 14901. https://doi.org/10.3390/su152014901.

Patah, M.F.A., Shafiee, N.S., Ismail, R., Bahar, A.M.A., Khan, M.M.A., Rak, A.E. & Awang, M., 2021. IOP Conf. Ser.: Earth Environ. Sci., 842, 012038. https://doi.org/10.1088/1755-1315/842/1/012038.

Project Blue, 2022. Rare Earths: Explaining Historical Volatility and Remaining Uncertainty in the Market. https://projectblue.com/blue/opinion-pieces/439/rare-earths:-explaining-historical-volatility-and-remaining-uncertainty-in-the-market.

Quek, L.X., Ghani, A.A., Chung, S., Li, S., Lai, Y., Saidin, M., Hassan, M.H.A., Ali, M.A.M., Badruldin, M.H. & Bakar, A.F.A., 2017. Mafic microgranular enclaves (MMEs) in amphibole-bearing granites of the Bintang batholith, Main Range granite province: Evidence for a meta-igneous basement in Western Peninsular Malaysia. Journal of Asian Earth Sciences, 143, 11-29. https://doi.org/10.1016/j.jseaes.2017.03.029.

Quek, L.X., Jamil, A., Ghani, A.A. & Saidin, M. 2015. Highly potassic melagranite of Bintang Batholith, Main Range Granite, Peninsular Malaysia. Current Science, 108, 2159-2163.

Ram, R., Becker, M., Brugger, J., Etschmann, B., Burcher-Jones, C., Howard, D., Kooyman, P.J. & Petersen, J., 2019. Characterisation of a rare earth element- and zirconium-bearing ion-adsorption clay deposit in Madagascar. Chemical Geology, 522(2019), 93-107. https://doi.org/10.1016/j.chemgeo.2019.05.011.

Robb, L.J., 2019. The geology of tin deposits with special reference to tin mineralisation in Peninsular Malaysia. Proceedings of the National Tin Conference 2019, Kuala Lumpur, Malaysia.

Sanematsu, K., Kon, Y., Imai, A., Watanabe, K. & Watanabe, Y., 2013. Geochemical and mineralogical characteristics of ion-adsorption type REE mineralization in Phuket, Thailand. Miner. Deposita, 48, 437-451.

Sanematsu, K. & Watanabe, Y., 2016. Characteristics and genesis of ion adsorption-type rare earth element deposits. In: Verplank, P.L. & Hitzman, M.W. (Eds.), Review In Economic Geology: Rare Earth and Critical Elements In Ore Deposits, 18. https://doi.org/10.5382/Rev.18.03.

Schmitt, R.A., Smith, R.H., Lasch, J.E., Mosen, A.W., Olehy, D.A. & Vasilevskis, J., 1963. Abundances of the fourteen rare-earth elements, scandium, and yttrium in meteoritic and terrestrial matter. Geochim. Cosmochim Acta, 27, 577-622.

Schmitt, R.A., Smith, R. & Olehy, D.A. 1964. Rare-earth, yttrium and scandium abundances in meteoritic and terrestrial matter – II. Geochim. Cosmochim Acta, 28, 67-86.

Sengupta, D. & Van Gosen, B.S., 2016. Chapter 4: Placer-type rare earth element deposits. In: Verplanck, P.L., & Hitzman, M.W. (Eds.), Rare earth and critical elements in ore deposits. Reviews in Economic Geology. Virginia, USA. 365 p.

Shafiee, N.S., Achmad Bahar, A.M. & Khan, M.M.A., 2020. Potential of Rare Earth Elements (REEs) in Gua Musang Granites, Gua Musang, Kelantan. IOP Conf. Series: Earth and Environmental Science, 549, 012027. https://doi.org/10.1088/1755-1315/549/1/012027.

Sun, S.S. & McDonough, W.F., 1989. Chemical and isotopic systematics of Oceanic Basalts: Implications for mantle composition and processes. In: Saunders, A.D. & Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geological Society London Special Publications, 42, 313-345.

Tampubolon, A., Syafri, I, Rosana, M.F. & Yuningsih, E.T., 2022. The occurrence of primary REE minerals and their paragenesis within S-type granite and quartz vein, South Bangka, Bangka Belitung Islands, Indonesia. Journal of Electrical Electronics Engineering, 1, 64-86.

Taniou, L., Basori, M.B.I. & Sanematsu, K., 2022. Geochemistry of Rare Earth Elements (REE) in the weathered crusts of volcanic rocks in the Serian area, Sarawak, Malaysia. Proceedings 17th GEOSEA and 34th National Geoscience Conference, Langkawi, Malaysia.

Umor, M.R., Ghani, A.A., Mohamad, H., Leman, M.S., Khin Zaw & Hussin, A., 2011. Re-evaluation of geochemical classification of the Western Belt, Central Belt and Eastern Belt granitoids, Malaysia Peninsular and their tectonic implications. Conference: The International Conference on Geology, Geotechnology and Mineral Resources of Indochina (GEOINDO 2011), Khon Kaen, Thailand

Wan Hassan, W.F. & Hamzah, M.S., 1999. Rare Earth Element patterns in some granitic rocks of Peninsular Malaysia. Bulletin of the Geological Society of Malaysia, 43, 513-528. https://doi.org/10.7186/bgsm43199952.

Wark, D.A. & Miller, C.F., 1993. Accessory mineral behaviour during differentiation of a granite suite: Monazite, xenotime, and zircon in the Sweetwater wash pluton, southeastern California, U.S.A. Chemical Geology, 110, 49–67. https://doi.org/0009-2541(93)90247-G.

Willbourn, E.S., 1925. A list of minerals found in British Malaya together with a description of their properties, composition, occurrences and uses. Journal of the Malayan Branch of the Royal Asiatic Society, 3, 57-100.

Wu, C., Huang, D. & Guo, Z., 1990. REE geochemistry in the weathered crust of granites, Longnan area, Jiangxi province. Acta Geol. Sinica, 3, 193–210.

Xiao, Z. & Zhang, W., 2024. Review of allanite: Properties, occurrence and mineral processing technologies. Green and Smart Mining Engineering, 1, 40-52. https://doi.org/10.1016/j.gsme.2024.04.004.

Xie, Y., Hou, Z., Goldfarb, R.J., Guo, X. & Wang, L., 2016. Chapter 6: Rare earth element deposits in China. https://doi.org/10.5382/Rev.18.06. In: Verplank, P.L. & Hitzman, M.W. (Eds.), Reviews in economic geology volume 18: Rare earth and critical elements in ore deposits. Society of Economic Geologists Inc., Littleton Colorado.

Yaraghi, A., Ariffin, K.S. & Baharun, N., 2016. Geochemistry and mobility of REE associated with weathered lateritic tin-granite profile. J. Malaysian Crit. Met., 1, 39-45.

Yaraghi, A., Ariffin, K.S. & Baharun, N., 2020. Comparison of characteristics and geochemical behaviors of REEs in two weathered granitic profiles generated from metamictized bedrocks in Western Peninsular Malaysia. Journal of Asian Earth Sciences, 199, 104385. https://doi.org/10.1016/j.jseaes.2020.104385.

Yeap, E.B., 1993. Tin and gold mineralizations in Peninsular Malaysia and their relationships to the tectonic development. Journal of Southeast Asian Earth Sciences, 8, 329-348.

Zhou, B., Li, Z. & Chen, C., 2017. Global potential of rare earth resources and rare earth demand from clean technologies. Minerals, 2017, 203-217. https://doi.org/10.3390/min7110203.

Zhou, X., Li, N., Niu, H., Jiang, Y., Yan, S., Yang, Y. & Fu, R., 2023. Hydrothermal alteration of allanite promotes the generation of ion-adsorption LREE deposits in South China. Ore Geology Reviews, 155, 105377. https://doi.org/10.1016/j.oregeorev.2023.105377.

Manuscript received 16 January 2025;
Received in revised form 17 April 2025;
Accepted 9 July 2025
Available online 29 May 2026