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Guidelines for rare earth elements (REE) exploration in Malaysia: A look into the rise of REE exploration in the country

Ahmad Izzat Zolkefli[1], Khairul Nazri Hj Yaakub[2], Abdul Hadi Abdul Rahman[3], Mahat Sibon[4], Fakhruddin Afif Fauzi[5,*], John Joseph Jinap[1], Shari Ismail[6], Yusari Basiran[3]

[1]Department of Mineral and Geoscience Malaysia Sarawak, Jln Wan Abdul Rahman, Kenyalang Park, 93712 Kuching, Sarawak, Malaysia
[2]Department of Mineral and Geoscience Malaysia Terengganu, PT3102K, Jln Sultan Sulaiman, 20200 Kuala Terengganu, Terengganu, Malaysia
[3] Department of Mineral and Geoscience Malaysia Headquarters, Level 9, Menara PjH, Jln Tun Abdul Razak, Precinct 2, 62100 Putrajaya, Malaysia
[4]Department of Mineral and Geoscience Malaysia Perak, Jln Sultan Azlan Shah, 31400 Ipoh, Perak, Malaysia
[5]Department of Mineral and Geoscience Malaysia Kedah / Perlis / P.Pinang, Jln Perak, Seberang Jalan Putra, 05150 Alor Setar, Kedah, Malaysia
[6]Department of Mineral and Geoscience Malaysia Pahang, Jln IM 4/1, Bandar Indera Mahkota, 25604 Kuantan, Pahang, Malaysia
*Corresponding author email address: afif@jmg.gov.my

Abstract: The ion-adsorption clay type rare earth elements deposit (IAC-REE) is recognised as one of Malaysia's strategic mineral resources due to its high global demand and economic potential. REEs are important raw materials for advanced sectors such as electronics, green technology, defence, catalysis, and automotive manufacturing. As IAC-REE exploration in Malaysia is relatively new and not yet well understood, the Department of Mineral and Geoscience Malaysia (JMG) has developed guidelines to assist its officers with the fundamentals of exploration and the interpretation of laboratory results. JMG has published two editions of these guidelines. The first edition, published in 2015, provides an overview of REE genesis and global deposit types, along with a step-by-step approach to conducting reconnaissance surveys. The second edition, published in 2023, is an updated version that focuses more on the genesis of IAC-REE deposits, provides guidance for subsequent exploration, and includes methods for calculating resources, while also addressing in-situ leaching (ISL) method and environmental concerns associated with irresponsible REE mining. These guidelines are based on reputable local and international journals and research studies. This paper aims to outline the contents of the second edition of the guidelines and highlight their relevance to the IAC-REE exploration conducted by JMG.

Keywords: Rare earth elements, ion adsorption clay, exploration guidelines, in-situ leaching, Malaysia

Abstrak: Endapan unsur nadir bumi jenis lempung jerapan ion (IAC-REE) diiktiraf sebagai salah satu mineral strategik Malaysia kerana permintaan global yang tinggi dan potensi ekonominya. REE merupakan bahan mentah penting dalam sektor berteknologi tinggi seperti elektronik, teknologi hijau, pertahanan, pemangkin, dan pembuatan automotif. Memandangkan penerokaan IAC-REE di Malaysia masih baharu dan kurang difahami, Jabatan Mineral dan Geosains Malaysia (JMG) telah membangunkan garis panduan bagi membantu pegawai-pegawai geosains memahami asas-asas aktiviti penerokaan dan tafsiran hasil makmal. JMG telah menerbitkan dua edisi garis panduan ini. Edisi pertama yang diterbitkan pada tahun 2015 merangkumi pengenalan kepada genesis REE dan jenis-jenis endapan di peringkat global, serta pendekatan langkah demi langkah untuk menjalankan tinjauan peninjauan awal. Edisi kedua, diterbitkan pada tahun 2023, merupakan versi terkini yang memberi fokus lebih mendalam kepada genesis endapan IAC-REE, panduan untuk kerja susulan penerokaan, serta kaedah pengiraan sumber. Ia turut merangkumi penerangan tentang kaedah perlombongan larut resap setempat (ISL) dan isu alam sekitar berkaitan perlombongan REE yang tidak bertanggungjawab. Garis panduan

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ini dibangunkan berdasarkan jurnal dan kajian penyelidikan tempatan serta antarabangsa yang berwibawa. Justeru, kertas kerja ini bertujuan menghuraikan kandungan edisi kedua garis panduan ini dan mengetengahkan kepentingannya dalam konteks penerokaan IAC-REE oleh JMG.

Kata kunci: Unsur nadir bumi, lempung jerapan ion, garis panduan eksplorasi, larut resap setempat, Malaysia

INTRODUCTION

Rare earth elements (REEs) are a group of 17 chemically similar metallic elements comprising the 15 lanthanides together with yttrium (Y) and scandium (Sc). They are generally divided into two subgroups based on atomic number and geochemical behaviour: light rare earth elements (LREEs)—from lanthanum (La) to samarium (Sm)—and heavy rare earth elements (HREEs)—from gadolinium (Gd) to lutetium (Lu), including yttrium.

REEs are critical components in the rapidly evolving global technology landscape. Their unique magnetic, catalytic, and luminescent properties make them indispensable in high-value sectors such as renewable energy, advanced electronics, defence systems, green technology, and electric vehicles. The growing global demand for REEs, particularly HREEs, has intensified exploration and development efforts worldwide, driven by their critical role in permanent magnets, electric vehicles, wind turbines, and advanced electronics.

REEs occur in a wide range of geological environments and mineral phases. Common primary REE-bearing minerals include monazite (rich in LREEs such as Ce, La, Nd, and Pr), xenotime (dominated by Y and HREEs including Dy, Er, and Yb), bastnäsite (a major host of LREEs, particularly Ce, La, Nd, and Pr), allanite (an LREE-bearing silicate containing Ce, La, and Nd), and zircon (typically enriched in Y and HREEs such as Yb, Er, and Dy). In tropical weathering environments, however, REEs are often enriched within ion-adsorption clays (IACs)—formed through prolonged chemical weathering and leaching of granitic rocks. These IAC-type deposits are of increasing interest due to their relative ease of extraction through ion-exchange leaching, which is more environmentally sustainable than conventional hard-rock mining.

In Malaysia, potential REE occurrences have been reported primarily in Terengganu, Kedah, Pahang, Negeri Sembilan, Perak, and Kelantan, where deeply weathered granitic bodies provide favourable conditions for the formation of IAC-type REE deposits. Malaysia's tropical climate and lateritic-granitic terrains share strong geological similarities with REE-producing regions in southern China, the world's leading producer of IAC-REEs.

Recognising this geological potential, the Department of Mineral and Geoscience Malaysia (JMG) initiated structured REE exploration programmes and took a pivotal step by developing REE Exploration Guidelines tailored to the Malaysian context. These guidelines serve to standardise exploration procedures, ensure scientific accuracy, and provide a solid foundation for responsible, effective, and environmentally sound REE exploration across the country.

The main objective of this paper is to present and describe the updated framework outlined in the second edition of Malaysia's Rare Earth Elements (REE) Exploration Guidelines developed by JMG. The paper aims to highlight key technical aspects of the guidelines—particularly those related to the exploration of ion-adsorption clay-type REE (IAC-REE) deposits—covering sampling methods, analytical procedures, data interpretation, and resource estimation approaches.

FIRST EDITION OF THE GUIDELINES (2015)

The first edition of the REE Exploration Guidelines, published in 2015, was a fundamental step in Malaysia's journey toward the development of rare earth resources (Figure 1). It introduced essential concepts related to REE deposit formation and described major types of occurrences, including alkaline igneous rocks, carbonatites and ion adsorption clay (IAC) deposit types. The issue also outlines general exploration workflows such as regional geological mapping, geochemical sampling, and preliminary geophysical surveys.

While it effectively laid the groundwork for REE exploration, the first edition provided only limited coverage of IAC-type deposits. Critical aspects such as the tropical weathering processes responsible for REE enrichment, specific sampling strategies for weathered profiles, and in-situ recovery techniques were only briefly mentioned. As fieldwork in Malaysia progressed, new findings—alongside a growing body of international research—highlighted the need for more in-depth and context-specific technical guidance, especially for REEs associated with weathered granitic terrains.

The seminal works by Banfield & Eggleton (1989), Bao & Zhao (2008) and Aubert *et al*. (2000) provided key insights into REE mobilisation, fractionation, and fixation during granite weathering. Studies by Compton *et al*. (2003) and Imai *et al*. (2008) further enhanced the understanding of REE behaviour in tropical soils and granitic crusts, while Sanematsu & Kon (2013) contributed crucial geochemical evidence from ion-adsorption deposits in southern China. Together with regional data from Thailand (Imai *et al*., 2008; Sanematsu *et al*., 2013) and global assessments by Kanazawa & Kamitani (2006),

Figure 1: Front covers of the first edition (left) and second edition of REE exploration guidelines (right), published by JMG.

these pre-2015 studies formed the foundational scientific framework underpinning the first edition of Malaysia's REE exploration guidelines, particularly in relation to REE mobilisation and fractionation during granite weathering.

Overall, these studies emphasized the importance of climate-driven weathering, horizon-specific REE enrichment, and the distinct mineralogical and geochemical characteristics of IAC deposits—factors that would become central in the second edition of the guidelines.

SECOND EDITION OF THE GUIDELINES (2023)

The second edition of the REE Exploration Guidelines, published in 2023, reflects the growing strategic importance of ion-adsorption clay (IAC)-type REE deposits in Malaysia and introduces significant refinements in exploration and extraction methodologies. A major improvement is the clearer and more systematic explanation of REE abstraction mechanisms within weathered profiles, which are classified into three distinct phases: ion-exchange, colloidal, and mineral-bound phases.

The ion-exchange phase represents the most accessible and economically significant component, accounting for approximately 60–90% of recoverable REEs. In this phase, REEs are

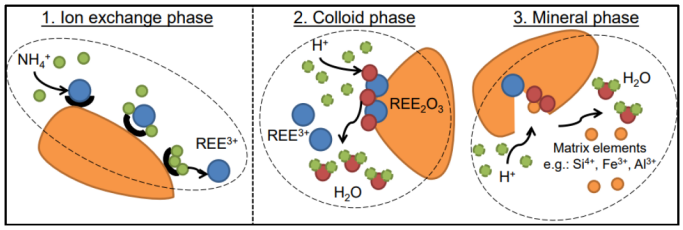

Figure 2: Illustration of the ion-exchange, colloid and mineral phases in ion-adsorption clay (after Voßenkaul *et al*., 2015).

weakly adsorbed onto clay mineral surfaces and can be extracted through cation-exchange reactions using monovalent cations, most commonly ammonium (NH_3^+) in the form of ammonium sulfate [$(NH_3)_2SO_4$]. The colloidal phase comprises REEs present as insoluble oxides, hydroxides, or organometallic complexes, which typically require mild to moderate acid leaching for recovery. In contrast, the mineral-bound phase consists of REEs locked within resistant primary or secondary mineral lattices and can only be liberated through aggressive treatments such as high-temperature alkaline processing or strong acid digestion (Figure 2).

Since the publication of the first edition in 2015, substantial advances have been made in understanding the mineralogical controls, adsorption mechanisms, and leaching behaviour of IAC-type REE deposits. These post-2015 studies provided the scientific foundation for the refinements incorporated into the second edition of the guidelines. In particular, Li *et al*. (2017; 2019) and Li & Zhou (2020) proposed integrated genetic models for regolith-

hosted REE deposits in South China, highlighting the critical role of clay mineralogy and progressive weathering in governing REE mobility and enrichment.

Earlier mineralogical studies, such as those by Papoulis *et al*. (2004a; 2004b), which documented kaolinization and monazite alteration processes, remain relevant as supporting background, while more recent works—including Verplanck (2017)—have further elucidated the role of fluids in REE transport and redistribution within weathered profiles.

From a processing perspective, recent studies by Voßenkaul *et al*. (2015) and Nawab *et al*. (2022) have advanced the understanding of REE speciation and recovery behaviour, including the use of oxalic acid and alternative leaching agents applicable to non-Chinese IAC deposits. These findings underpin best-practice recommendations for environmentally responsible extraction methods suited to Malaysia's tropical regolith conditions.

Overall, the second edition of the guidelines promotes a more focused mineralogical and geochemical approach to IAC-REE exploration and recovery, aligning Malaysia's REE exploration framework with contemporary international standards and evolving global best practices.

IN-SITU LEACHING (ISL) TECHNIQUES

The second edition guideline contains details procedures for ISL, a minimally invasive mining method suitable for IAC-REEs. Site preparation begins with shallow borehole drilling (1.5–3.0 m depth, at 2–3 m spacing). Horizontal collection trenches or pipes are constructed parallel to the bedrock to direct the pregnant solution into a containment area. Lixiviants solution such as ammonium sulphate or other monovalent salts are injected, and flocculants such as polyacrylamide (PAM) are added to remove impurities such as Al and Zn. During the in-situ leaching (ISL) process, the use of ammonium sulphate [$(NH_4)_2SO_4$] as a lixiviant leaching agent triggers a cation exchange reaction, in which ammonium ions (NH_4^+) are adsorbed by clay minerals in the soil, releasing rare earth elements (REEs) into solution as REE sulfates. The reaction can be simplified as follows:

$$2\ \text{clay-REE} + \underset{\text{(ammonium sulfate)}}{3(NH_4)_2SO_4} \rightarrow 2\ \text{clay-}(NH_4)_3 + \underset{\text{(REE sulfate)}}{REE_2(SO_4)_3}$$

The ISL method is environmentally friendly but geographically limited; it is best implemented in hilly terrain. Comprehensive site investigations—including geotechnical, hydrogeological, and mineralogical studies—are essential to assess the REE grade, leaching efficiency, and potential risks such as groundwater contamination and slope instability.

Precipitation and recovery

The guidelines examine several precipitation agents for the recovery of REEs from the pregnant leach solution. Oxalic acid is the most commonly used due to its strong affinity for REEs and its ability to produce high-purity REE oxalates. However, it is also known to be carcinogenic and poses environmental health concerns. In contrast, ammonium bicarbonate is a more practical and environmentally safer alternative for large-scale operations, providing REE carbonates along with recyclable by-products such as ammonium sulphate. The chemical reactions that take place during REE precipitation with oxalic acid and ammonium bicarbonate are as follows:

a) $\underset{\text{(REE sulfate)}}{REE_2(SO_4)_3} + \underset{\text{(oxalic acid)}}{3H_2C_2O_4} + 10H_2O \rightarrow \underset{\text{(hydrated REE sulfate)}}{REE_2(C_2O_4)_3.10H_2O} + \underset{\text{(sulfuric asid)}}{H_2SO_4}$

b) $\underset{\text{(REE sulfate)}}{REE_2(SO_4)_3} + \underset{\text{(ammonium bicarbonate)}}{3(NH_4)_2CO_3} \rightarrow \underset{\text{(REE carbonate)}}{REE_2(CO_3)_3} + \underset{\text{(ammonium sulfate)}}{3(NH_4)_2SO_4}$

Oxalic acid and ammonium bicarbonate exhibit contrasting environmental, economic, and processing characteristics as precipitants for REE recovery from pregnant leach solutions. Oxalic acid precipitates REEs as insoluble oxalates through a highly selective mechanism, producing high-purity products due to its strong affinity for REEs and limited co-precipitation of impurities such as Fe, Al, and Mn (Han, 2020). However, its application involves higher reagent costs, strict pH control under acidic conditions (pH ~1–2), and the generation of acidic by-products that increase waste management and environmental burdens, particularly at large scales.

In contrast, ammonium bicarbonate precipitates REEs as carbonates and offers a more cost-effective and environmentally benign option for bulk operations, with simpler process control and fewer persistent waste residues due to its decomposition into CO_2, NH_3, and H_2O. Nevertheless, the resulting REE carbonates generally exhibit lower purity owing to co-precipitation of elements such as Ca and Mg, which may require additional downstream purification if high-grade products are desired. In line with Malaysia's REE mining standard operating procedures (SOPs), the use of ammonium-based reagents—particularly ammonium sulphate—is mandated in preference to oxalic acid to minimise environmental risks and ensure regulatory compliance.

Accordingly, ammonium-based systems are favoured for large-scale and environmentally responsible REE operations in Malaysia, while oxalic acid remains more suitable for controlled laboratory or small-scale applications where high selectivity and product purity are prioritised.

Impurity removal

Within the precipitation and recovery process, impurity removal is achieved through controlled pH manipulation, enabling the staged separation of impurities and rare earth elements.

Ammonium bicarbonate functions not only as a precipitating agent but also as a pH regulator, progressively increasing the solution pH with increasing reagent dosage. At an approximate 1:1 molar ratio of ammonium bicarbonate to rare earth elements, the solution pH rises to around 5, promoting the selective precipitation of impurities such as Fe and Al.

Further addition of ammonium bicarbonate, at molar ratios exceeding 3, increases the pH to above 8, triggering the precipitation of REEs as carbonates. To maximise REE recovery, a molar ratio of approximately 4:1 between ammonium bicarbonate and REO is typically applied.

Following precipitation, the recovered REE carbonates are calcined at an optimum temperature of about 900 °C to produce rare earth oxides (REOs).

FOLLOW-UP EXPLORATION AND SAMPLING TECHNIQUES

The second edition emphasizes rigorous and systematic sampling protocols. Soil samples are collected at consistent depth intervals (e.g., every 1 m) using control holes, with sampling conducted on a regular grid at approximately 200 m spacing, and focused on the lower B to upper C horizons—zones generally recognised as the main REE enrichment layers (Figure 3), as supported by numerous studies including Yaraghi *et al*. (2020) and Ubaidillah *et al*. (2024). Soil samples are organized by depth, with colour classified according to the Munsell soil colour chart. Notable mineral grains, such as quartz, feldspar and biotite, are also recorded (Figure 4). All

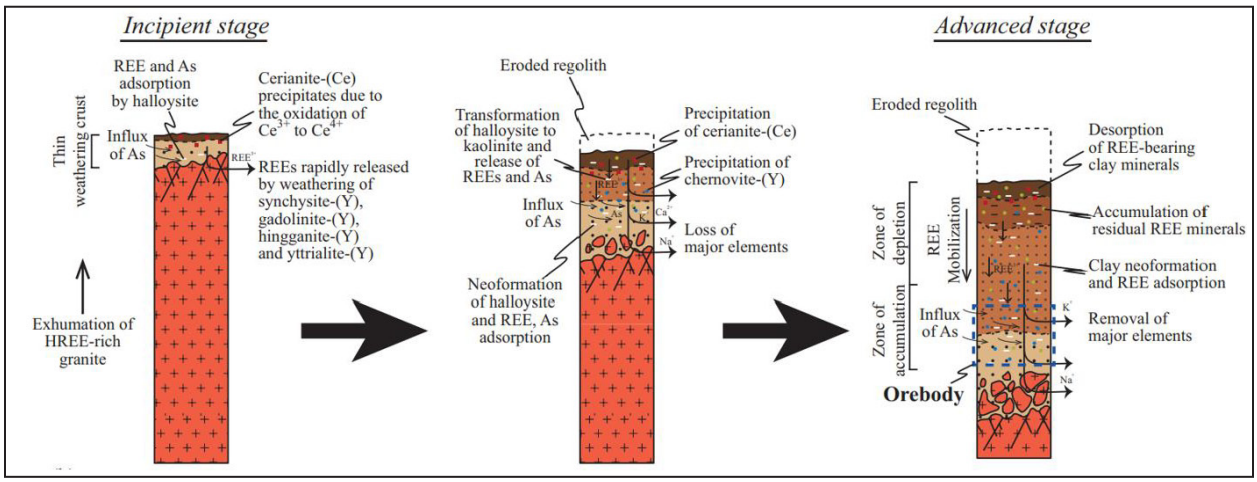

Figure 3: A schematic model illustrating the development of the weathering profile and the formation of the REE enrichment zone within the lower B to upper C horizons, based on the Zudong deposit as referenced in this guideline (adapted from Li *et al.*, 2019).

Figure 4: Soil samples arranged by depth for visual inspection. Observations include color determination using the Munsell soil color chart and identification of mineral grains.

observations are systematically recorded on a standardized sheet (Figure 5).

Fresh rock samples are collected to determine background REE concentrations, while concentrates from the weathered profile are analysed to identify associated REE-bearing minerals.

Soil samples are air-dried prior to sieving, preferably in the field, mainly to reduce moisture content and sample weight for ease of transport and subsequent processing. Although oven-drying in the laboratory provides better temperature control and consistency, field drying is considered more cost-effective and time-efficient for JMG's large-scale exploration activities, particularly in remote or high-sampling-density areas.

Sieving is performed to remove coarse quartz and possible REE-bearing minerals, thereby concentrating the finer clay-sized fraction that better represents ion-adsorbed REE content. This approach, adopted by JMG, is based on internal orientation studies conducted prior to detailed exploration. The objective was to obtain representative REE values for IAC deposits while minimising the influence of mineral-bound REE phases and coarse detrital minerals such as quartz, which are known to contain negligible REE concentrations.

Laboratory analyses for soil samples should include:

- XRF: for major oxides (including SiO_2, $Al2O_3$, Fe_2O_3, CaO, K_2O, Na_2O, MgO, MnO and TiO_2)
- LOI: to estimate total mass lost upon ignition at high temperature (950°C).
- LA-ICP-MS: for REE (La to Lu), Th, and U concentration

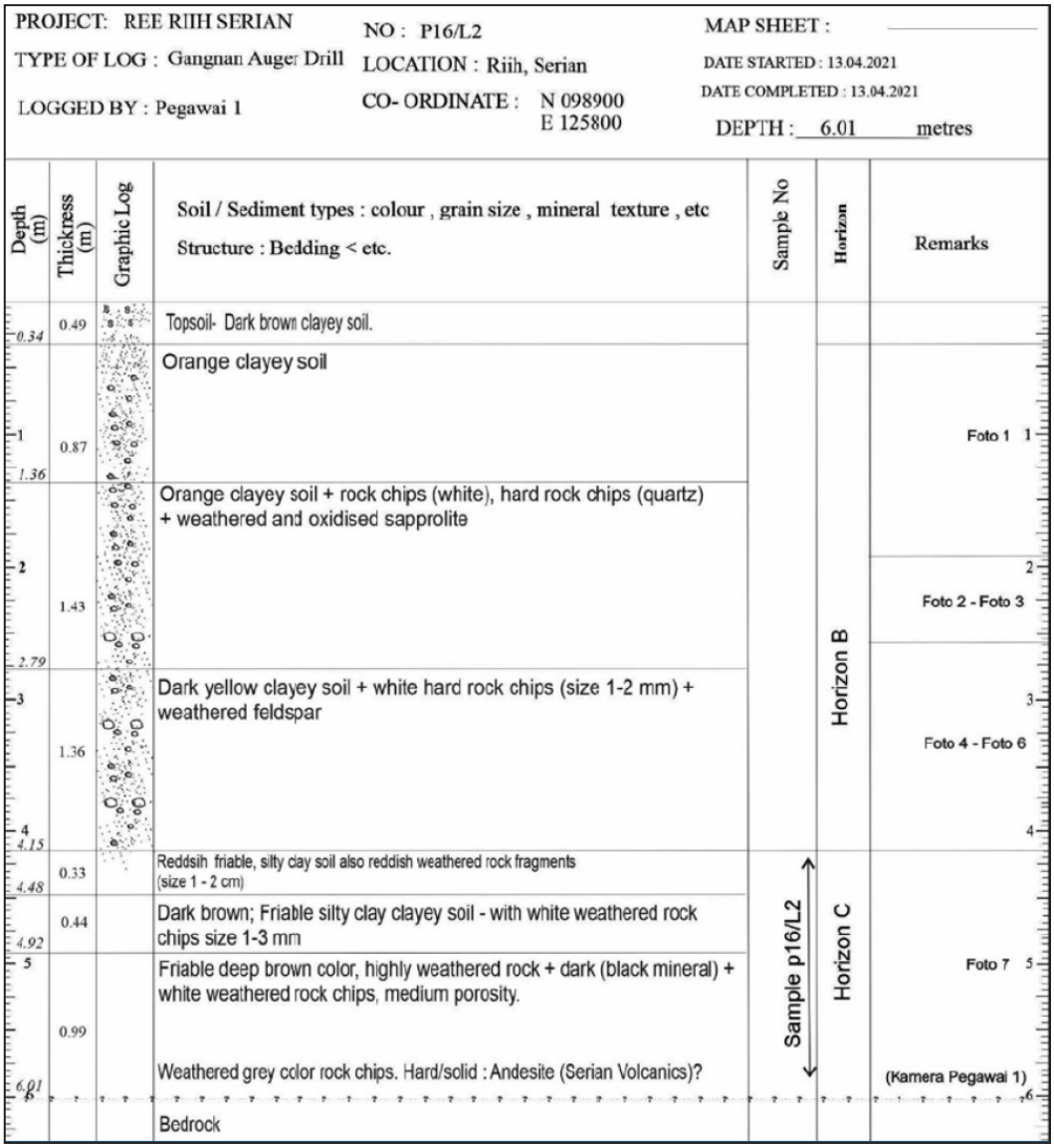

Figure 5: Example of a soil sampling log sheet, documenting depth intervals, soil color, texture, and mineral constituents observed.

- XRD: to identify clay and REE minerals
- SEM/FESEM: for mineral morphology (optional)

Rock samples are subjected to similar tests with additional petrographic analysis.

Concentrate samples are obtained through panning of soil materials that previously showed exceptionally high REE concentrations. This procedure aims to verify whether the elevated REE values are associated with ion-adsorbed clays or influenced by the presence of heavy REE-bearing minerals. The concentrates are then analysed using QME to quantify REE-bearing mineral phases and validated through XRF, XRD, and SEM analyses.

RADIOACTIVITY

Thorium (Th) and uranium (U) concentrations are also analysed to confirm the low radioactivity of IAC-REE deposits, a characteristic generally expected for this deposit type. In Malaysia, naturally occurring radioactive material (NORM) is regulated under the Atomic Energy Licensing (Radioactive Waste Management) Regulations 2011. According to Schedule 2 of the regulations, materials with a radioactivity content of less than 1 Bq/g are classified as NORM and are not subject to regulatory control. This threshold corresponds to approximately 246.5 ppm for Th-232 and 80.9 ppm for U-238.

SUPPORTIVE STUDIES AND FIELD TESTS

Leaching and precipitation in the field tests provide quick, indicative assessments of REE potential. In leaching tests, 0.3 M ammonium sulphate is used to extract REEs as REE sulphates. Oxalic acid or ammonium bicarbonate is added to precipitate REE oxalates and carbonates, respectively. Increased turbidity during oxalate addition indicates a higher REE content.

DATA PROCESSING AND INTERPRETATIONS

Data interpretation includes statistical analysis, calculation of Ce, Eu, and La/Yb anomalies, and construction of chondrite-normalized REE diagrams. Representative ICP-MS results showing characteristic Ce, Eu, and La/Yb anomalies are presented in Table 1.

The IAC-REE enrichment layer in weathered profiles is commonly characterised by relatively lower or negative Ce anomalies compared to the upper and lower parts of the profile, reflecting downward migration and accumulation of trivalent REEs during oxidative weathering (Compton *et al*., 2003; Bao & Zhao, 2008; Sanematsu *et al*., 2013). Positive Ce anomalies toward the D horizon (Table 1) likely reflect parent-rock inheritance and reduced Ce mobility under less weathered conditions, where Ce is preferentially retained as insoluble Ce^{4+} associated with Fe–Mn oxides or cerianite.

Negative Eu anomalies generally reflect the geochemical signature inherited from granitic parent rocks, where Eu^{2+} is preferentially incorporated into plagioclase during magmatic crystallisation, leading to Eu depletion in the residual melt (Sun & McDonough, 1989; Braun *et al*., 1990). This magmatic signature is typically preserved during weathering and is consistently observed in IAC-REE profiles (Imai *et al*., 2008; Sanematsu *et al*., 2013).

La/Yb ratios indicate the degree of LREE–HREE fractionation, with higher values reflecting preferential LREE enrichment due to the greater weathering susceptibility of LREE-bearing fluorocarbonates relative to more resistant HREE-bearing minerals such as zircon (Sanematsu & Kon, 2013).

Chondrite-normalized REE patterns (Sun & McDonough, 1989) generally show similar trends between rock and soil samples, with consistently higher REE concentrations in soils, reflecting geochemical inheritance from the bedrock and enrichment within the weathered zone. Deviations from these patterns may reflect heterogeneity in the geochemical characteristics of the weathered profile, potentially arising from variations in parent rock composition, differential weathering intensity, localized reworking of the soil profile, or minor post-depositional alteration.

MAPPING AND ECONOMIC ASSESSMENT

Spatial interpolation of rare earth element (REE) concentration data using Kriging or Inverse Distance Weighting (IDW) in GIS software allows for the creation of total REE (TREE), heavy REE (HREE), and light REE (LREE) distribution maps. These visualisations serve as a guide for further work and resource prioritisation (Figure 6).

Initial surveys indicate REE concentrations over 300 ppm are considered promising for further investigation. Areas with more than 500 ppm are considered suitable for potential exploitation.

The resource estimation assumes a bulk density of 1.5 t/m^3 for disturbed soils. In IAC-REE deposits, approximately 65% of the REE content is recoverable through leaching and precipitation, whereas the rest remains bound in supergene or refractory residual minerals (after Li *et al*., 2019). Detailed estimations can be refined using sector-based calculations or Thiessen polygon models.

Resource estimation for IAC-REE is classified as measured when sampling is conducted at relatively close spacing—typically between 50 m and 200 m—allowing reliable estimates of tonnage, density, grade, and mineral content with a high degree of confidence. If the sampling spacing exceeds 200 m, up to 500 m, the classification is downgraded to an indicated resource due to increased uncertainty in geological continuity and estimation accuracy. In general, the estimation focuses on the lower B to upper C horizons, where REE accumulation is typically higher, as supported by numerous studies. However, this may vary case by case depending on the local geological setting and profile depth.

Table 1: Examples of ICP-MS results and Ce, Eu, and La/Yb anomalies, in ppm.

Sample	Horizon	Th	U	Sc	Y	LREE						TLREE
						La	Ce	Pr	Nd	Sm	Eu	
KS901B	B	154.00	23.50	10.80	94.80	283.00	430.00	56.50	234.00	56.30	1.67	1,061.47
KS902B	B	213.00	15.50	12.10	90.30	324.00	565.00	70.00	291.00	58.30	2.06	1,310.36
KS903B	B	271.00	37.60	12.40	241.00	348.00	509.00	84.90	380.00	90.40	2.81	1,415.11
KS904B	B	236.00	11.40	11.90	118.00	350.00	765.00	80.80	333.00	59.80	2.81	1,591.41
KS905B	B	201.00	19.10	11.90	115.00	307.00	507.00	75.60	317.00	60.30	3.63	1,270.53
KD9104	C	144.00	16.90	14.60	112.00	210.00	349.00	52.50	192.00	38.20	2.05	843.75
KD9105	C	137.00	21.80	14.40	120.00	205.00	310.00	43.70	159.00	32.30	1.86	751.86
KD9106	C	204.00	29.90	17.00	90.00	180.00	408.00	48.60	139.00	31.90	1.80	809.30
KD9107	C	258.00	31.00	16.20	70.30	170.00	428.00	50.60	124.00	30.50	1.64	804.74
KR901	D (Rock)	89.70	18.10	5.92	53.40	150.00	251.00	21.90	94.30	19.80	1.00	538.00

Table 1: Continued.

Sample	Horizon	HREE								THREE	TREE	Anomaly		
		Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			Ce/Ce*	Eu/Eu*	La/Yb
KS901B	B	26.80	3.45	19.60	3.33	9.40	1.19	7.90	1.19	167.66	1,239.93	0.82	0.15	35.82
KS902B	B	31.70	3.39	17.80	2.86	7.85	0.91	7.09	0.82	162.72	1,485.18	0.90	0.19	45.70
KS903B	B	53.70	7.63	41.20	7.06	19.00	2.62	16.50	2.42	391.13	1,818.64	0.71	0.14	21.09
KS904B	B	34.10	4.37	24.50	4.28	11.70	1.52	9.47	1.28	209.22	1,812.53	1.10	0.22	36.96
KS905B	B	33.50	4.45	24.80	4.33	12.00	1.53	9.50	1.28	206.39	1,488.82	0.80	0.29	32.32
KD9104	C	24.90	4.45	23.20	4.76	12.10	2.02	12.10	1.88	197.41	1,055.76	0.80	0.20	17.36
KD9105	C	22.80	4.39	23.70	4.97	12.60	2.08	12.30	1.89	204.73	970.99	0.79	0.20	16.67
KD9106	C	22.20	4.26	23.10	4.93	11.80	2.00	12.20	1.85	172.34	998.64	1.05	0.20	14.75
KD9107	C	20.40	3.68	20.00	4.20	10.00	1.69	10.40	1.57	142.24	963.18	1.11	0.20	16.35
KR901	D (Rock)	14.10	1.87	11.50	2.09	6.11	0.65	4.82	0.59	95.13	639.05	1.06	0.21	31.12

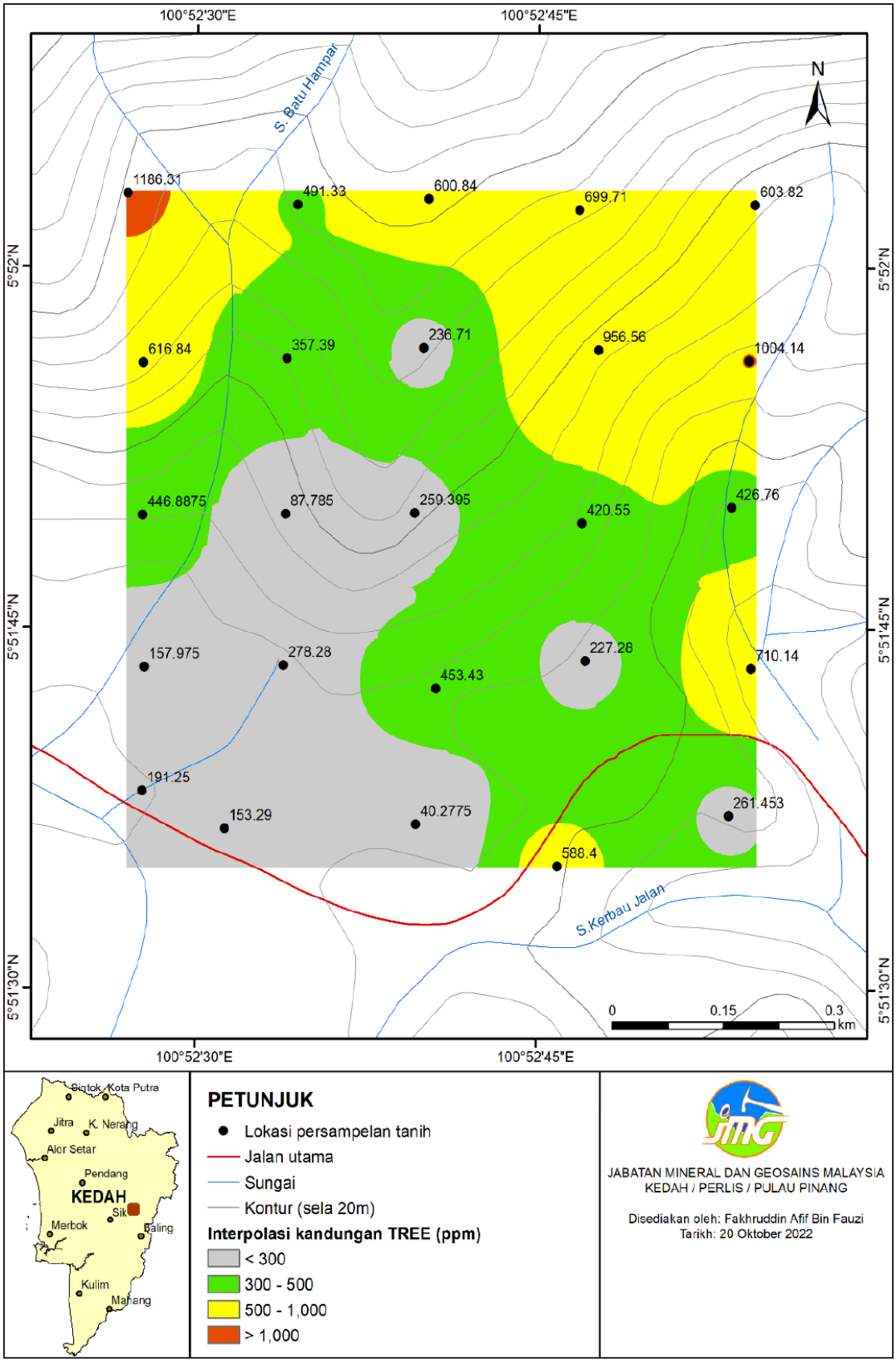

Figure 6: Example of a total REE (TREE) distribution map generated using Kriging interpolation, based on the average REE content at each sampling point.

The general formula for estimating a measured IAC-REE resource, based on a 1 km² study area adopted by JMG, is as follows:

Total density of studied weathered profile (soils) = Study area (m^2) x average depth (m)
= 1,000 m x 1,000 m x 10 m
= 10,000,000 m^3

Average TREE content = 609.89 ppm
= 0.060989%
= 0.60989 kg/tonne

Measured resource of IAC-REE = 10,000,000 m^3 x 1.5 tonne/m^3 x 0.60989 kg/tonne x 65%
= 5,946,428 kg
= 5.946 metric tonne / km^2
= 24 metric tonne / acre

JMG applies the measured resource classification, instead of inferred or estimated because exploration is conducted within a confined 1 km² study area using closely spaced sampling grids (50–200 m). This approach provides a high level of confidence in estimating tonnage, density, grade, and mineral content.

CONCLUSION

The second edition of Malaysia's REE Exploration Guidelines represents a major advancement in the nation's geoscientific capability and governance of critical mineral resources. By focusing on ion-adsorption clay (IAC)-type deposits and aligning exploration methodologies with international best practices, the guidelines provide an essential framework for geoscientists, policymakers, and the mining industry.

This study underscores the importance of establishing systematic, science-based exploration procedures for IAC-REE deposits in Malaysia. The guidelines developed by JMG serve as a national reference for standardising exploration workflows, analytical techniques, and data interpretation. By aligning local practices with global standards, these guidelines enhance the accuracy, efficiency, and environmental accountability of REE exploration activities.

While comprehensive, the guidelines are not intended to be final or exhaustive. They remain open to further improvement through collaboration, feedback, and contributions from external experts, research institutions, and industry stakeholders. Such continuous enhancement will ensure that Malaysia's REE exploration framework evolves in line with new scientific insights, technological advancements, and global sustainability standards.

Overall, the findings strengthen Malaysia's technical capacity in critical mineral exploration and support the nation's strategic goal of sustainable resource development. The implementation of these guidelines ensures that REE exploration is conducted in a scientifically robust, transparent, and environmentally responsible manner—laying the groundwork for future innovation and responsible exploitation of Malaysia's REE potential.

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AUTHORS CONTRIBUTION

AIZ and FAF conceptualized the paper. KNHY, AHAR, MS, JJJ, SI, and YB contributed to data gathering, drafting, and critical revisions. All authors reviewed and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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