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An Evidence-Constrained Four-Domain Exploration Framework for Rare Earth Elements in The Bangka Belitung Tin-Granite System

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ABSTRACT

Rare earth element (REE) enrichment in the Bangka Belitung tin province occurs in genetically and technologically distinct materials that require different exploration and processing tests. This study develops an evidence-constrained framework that integrates fresh granite, weathered granite, placer/alluvium, and tin-processing residues without merging non-comparable geochemical values. The analysis separates primary accessory-mineral-hosted, residual mineral-grain, ion-exchangeable clay-associated, mechanically concentrated, and anthropogenically concentrated REEs. Site-specific datasets were evaluated by sample medium, analytical basis, mineral host, spatial support, process diagnosis, recovery evidence, and U-Th/NORM risk. Weathered profiles show systematic enrichment toward lower horizons: reported total REE concentrations increase from 156-188 to 196-268 ppm at Toboali and from 230-330 to 342-450 ppm at Air Gegas. Mineralogical studies identify monazite as the principal Ce-rich light-REE host and xenotime as a Y-heavy-REE host across primary, placer, concentrate, and tailings materials. Diagnostic leaching from South Bangka demonstrates that part of the REE inventory is extractable, but strong-acid recoveries cannot be generalized as evidence of low-intensity ion-exchange recovery. The ordinal screening assigns weathered granite the highest geological prospectivity but only moderate evidence confidence; tailings and placers remain attractive near-surface domains with greater heterogeneity and radiological uncertainty. Remote sensing is retained as a proxy for regolith, drainage, and disturbed ground, not as direct REE detection. The framework provides a reproducible basis for prioritizing field verification while preventing conceptual prospectivity from being misreported as a resource or economic valuation.

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INTRODUCTION

Decarbonization technologies have increased demand for individual REEs whose value is controlled by mineralogy, recoverability, and supply-chain concentration rather than by total REE abundance alone. Nd, Pr, Dy, and Tb are central to high-performance permanent magnets, whereas La, Ce, and Y support catalysts, polishing materials, ceramics, and specialized alloys. The Bangka Belitung tin province is therefore relevant not simply because REEs have been reported, but because granitic source rocks, deeply weathered regolith, placer systems, and mining residues may contain different REE hosts with contrasting extraction and environmental constraints (Geological Agency 2022; Johnston 2026).

The study treats REE assessment as an applied resource-geoscience problem. Regional geology, geochemistry, mineralogy, geomorphology, remote sensing, and early value-risk analysis are integrated to reduce exploration uncertainty, but each dataset is interpreted according to its actual evidentiary capability. In particular, surface spectral responses and lineaments are used to guide verification, not to substitute for mineralogical, geochemical, or recovery data (Suliantara et al., 2021; Susantoro et al., 2023; Widarsono et al., 2021).

Bangka Belitung occupies the southeastern segment of the Southeast Asian Tin Belt, a metallogenic province extending from Myanmar and Thailand through Peninsular Malaysia to western Indonesia. Bangka granites are commonly described as S-type and peraluminous intrusions related to tin mineralization, with accessory monazite, xenotime, zircon, and other REE-bearing phases. This regional setting provides the primary source context for Sn-REE association (Katili 1967; Cobbing et al., 1986; Ng et al., 2017; Wang et al., 2021).

Bulk grade is an incomplete measure of REE potential. Extractability depends on whether REEs occur in monazite, xenotime, zircon, or other discrete minerals; remain as resistant residual grains; occupy exchangeable sites on kaolinite, illite, or Fe-Mn phases; or are mechanically concentrated in placers and processing residues. Mineral liberation, leach response, LREE-HREE distribution, and U-Th deportment therefore determine the appropriate processing route and environmental burden (Syafrizal et al., 2024; Tampubolon et al., 2024; Septiarani et al., 2026).

Figure 1 provides a regional geological and structural reference from northern Bangka. Because the mapped faults and lineaments are not accompanied here by orientation statistics, density analysis, or spatial tests against South Bangka REE samples, they are treated only as evidence of a possible regional structural influence. The figure does not demonstrate a causal structural control on the Air Gegas-Toboali targets.

The central exploration question is how REE-bearing material is redistributed through a linked source-weathering-transport-processing system. REEs may remain in accessory minerals in fresh granite, become residually concentrated during mass loss, occur in exchangeable forms on clay or Fe-Mn phases, accumulate mechanically in placers, or become anthropogenically concentrated in tin-processing residues.

These enrichment styles require different evidence. Whole-rock or bulk ΣREE values can indicate enrichment but cannot by themselves identify the mineral host, prove ion adsorption, establish recovery, or demonstrate continuity. This synthesis therefore separates direct mineralogical or leaching evidence from literature-based geological inference and from hypotheses that still require field testing.

Direct evidence from South Bangka weathering profiles includes multi-depth sampling and mineralogical-geochemical analyses showing that lower regolith horizons may preserve REE-bearing residual minerals and localized enrichment (Tampubolon et al., 2024; Agung et al., 2024). More recent work at Keposang-Toboali adds mineralogical and diagnostic-leaching evidence for REEs associated with kaolinite-bearing material, but site-specific leach behaviour should not be generalized to all weathered granite without comparable tests (Septiarani et al., 2026).

Tin tailings and related residues provide a circular-economy target because material has already been excavated and partly sorted. However, the same monazite- and xenotime-bearing fractions may contain Th and U, creating NORM, licensing, waste-management, and product-penalty issues. Representative sampling, mineral separation, and radiological characterization are therefore essential before any recovery claim (Zglinicki et al., 2021; Zglinicki et al., 2022; Ngadenin et al., 2023).

Previous studies have already documented Air Gegas, Toboali, weathered-granite enrichment, cassiterite-associated monazite-xenotime, placer concentration, and REE-bearing tin residues. The research gap is therefore not the first recognition of these occurrences, but the absence of a single evidence framework that compares distinct materials without conflating their geochemical bases, mechanisms, extractability, and uncertainty.

The contribution of this study is an evidence-constrained four-domain framework that compares fresh granite, weathered granite, placer/alluvium, and tin-processing residues while retaining the distinction between primary mineral-hosted, residual, ion-exchangeable, mechanically concentrated, and anthropogenic enrichment. The objectives are to (1) harmonize site-specific evidence without combining incompatible

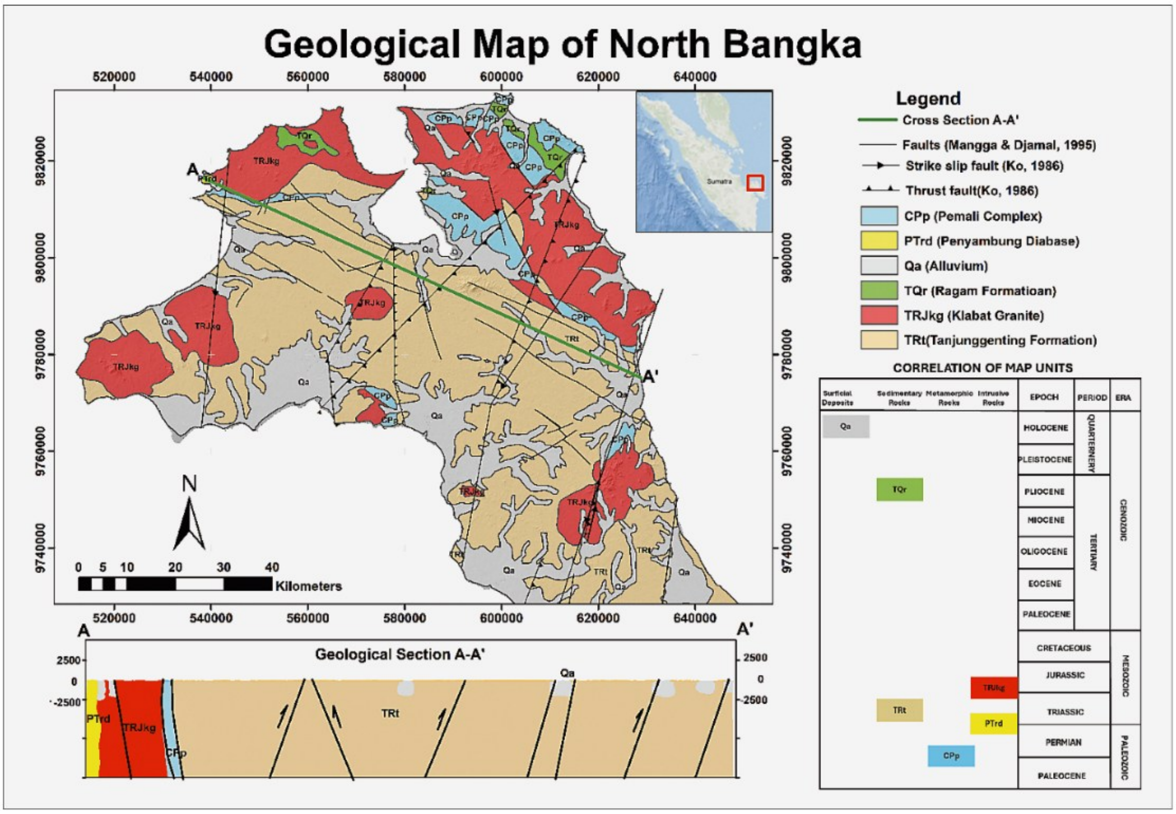

Figure 1. Geological map of northern Bangka showing lithological units and geological structures. Source: Hutami et al. (2026), modified after Mangga and Djamal (1994) and Ko (1986).

analytical bases, (2) quantify geological prospectivity separately from evidence confidence, and (3) define the mineralogical, metallurgical, spatial, and radiological tests required to advance each domain. The output is an ordinal exploration-screening model rather than a resource estimate or calibrated spatial prediction.

This design also clarifies the role of transferable Indonesian geoscience workflows. Geological maps, DEM interpretation, remote sensing, geochemistry, and field verification can efficiently narrow early-stage search areas, but their evidentiary meaning depends on data provenance, resolution, sampling support, and independent ground verification (Suliantara et al., 2021; Susantoro et al., 2023; Widarsono et al., 2021).

In this REE context, Sentinel-2 or Landsat responses to clay, iron oxides, moisture, drainage, and disturbed ground are treated as process or land-surface proxies. They can support mapping of weathering patterns, placer pathways, or tailings footprints, but they are not direct measurements of REE concentration and cannot validate mineral hosts without field and laboratory data (Purwadi et al., 2020; Susantoro et al., 2024).

Regionally, Bangka tin granites belong to the Main Range granite province and are mainly Late Triassic in age. U-Pb zircon evidence indicates major emplacement around 225-220 Ma, consistent with post-collisional magmatism following regional Paleotethyan evolution (Ng et al., 2017; Wang et al., 2021). This provides source-rock context rather than proof of recoverable REE mineralization at a specific site.

Bangka is characterized by low to gently undulating relief, local granite ridges, denudational plains, foot-slope zones, alluvial plains, swamps, and broad coastal areas. This geomorphology may preserve regolith and redistribute heavy minerals into fluvial, coastal, and tailings environments; the degree of concentration must nevertheless be demonstrated by stratified sampling (Ko 1986; Purwadi et al., 2020; Tampubolon et al., 2024).

Figure 2 illustrates the vertical heterogeneity of South Bangka alluvium. It supports a sampling hypothesis - not a grade prediction - that surface sand, clay-rich intervals, gravelly horizons, and basal heavy-mineral layers should be sampled separately rather than composited as one medium (Aminuddin et al., 2026).

Table 1 organizes four target domains - fresh granite, weathered granite, placer/alluvium, and tin tailings - together with metasedimentary or sedimentary cover as regional context. The distinction is important because source mineralization, residual enrichment, ion adsorption, hydraulic sorting, and processing residues cannot be ranked using a single unqualified concentration scale.

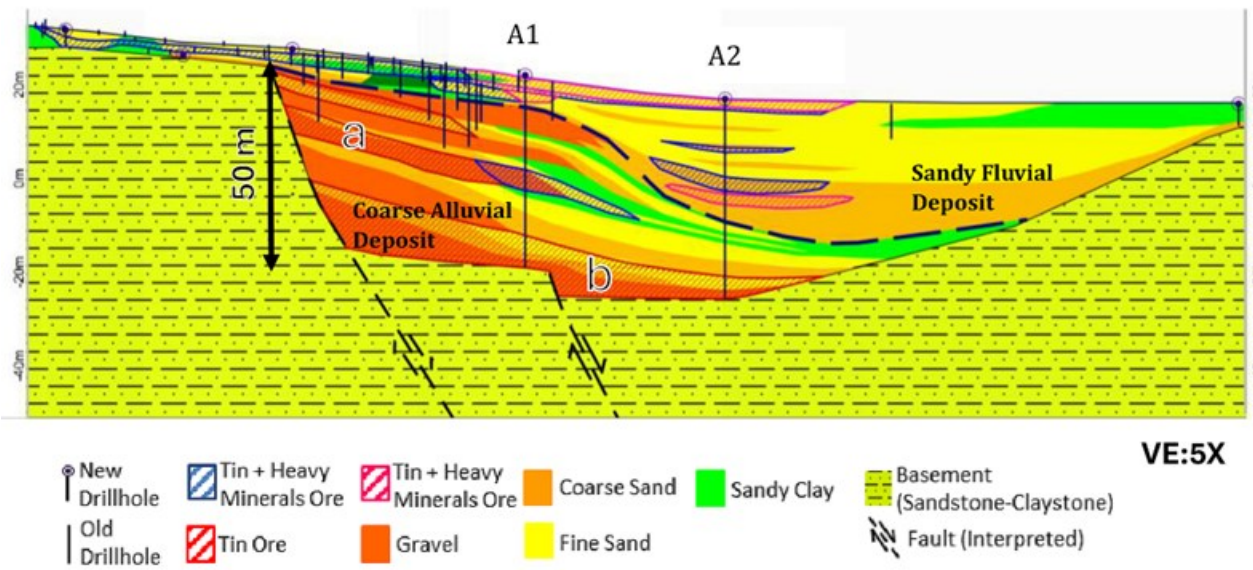

Figure 2. Stratigraphic cross-section of alluvial deposits in South Bangka. Source: Aminuddin et al. (2026).

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Table 1. Geological units and domains relevant to the Bangka Belitung REE system.

No.	Unit/domain	Main characteristics	Relevance to REEs
1	Bangka granite	S-type granite, cassiterite-bearing, with REE accessory minerals	Primary Sn–REE source and altered-rock target
2	Granite weathering profile	Saprolite, B/C horizons, kaolinitic clay, residual heavy minerals	Secondary residual enrichment domain
3	Placer/alluvium	Foot slopes, fluvial deposits, flood plains, coastal accumulations	Mechanical trap for heavy minerals
4	Tin tailings	Post-processing material and pre-concentrated heavy minerals	Near-surface REE/HREE opportunity with environmental constraints
5	Metasedimentary/sedimentary cover	Phyllite, schist, sandstone, siltstone, conglomerate	Provides contextual control on morphology, drainage, and secondary transport

Where favorable domains overlap, such as preserved weathered granite near foot-slope traps or residues derived from monazite-xenotime-bearing source material, the overlap is treated as a literature-based exploration inference. It does not substitute for measured continuity, representative grade, mineral deportment, recovery testing, or radiological assessment.

METHODOLOGY

This study used a structured, problem-oriented evidence synthesis coupled with an ordinal domain-screening matrix. The unit of analysis was the material domain rather than the publication: fresh or altered granite, weathered granite, placer/ alluvium, and tin-processing residues. Four questions guided data extraction: (1) which REE host is demonstrated; (2) which enrichment mechanism is supported; (3) what spatial or stratigraphic continuity is documented; and (4) which recovery and U-Th/NORM constraints have been tested. Evidence quality was judged from analytical design, sample support, and relevance to the stated process.

The source-rock framework was anchored to Ng et al. (2017), who used U-Pb zircon geochronology and whole-rock geochemistry to relate Bangka granitoids to the Main Range granite province, and to Syafrizal et al. (2024), who characterized 51 primary, placer, concentrate, and tailings samples by microscopy, XRD, SEM, EPMA, and ICP-MS. Weathering and ion-adsorption evidence was taken from Tampubolon et al. (2024), who combined XRF, ICP-MS/OES, XRD, SEM-EDX, EPMA, and leaching on Toboali and Air Gegas profiles; Agung et al. (2024), who examined mineralogical and geochemical changes within the Toboali weathered crust; and Septiarani et al. (2026), who applied quantitative mineralogy and diagnostic leaching to a composite from five Keposang-Toboali locations. Tailings and near-surface evidence was constrained by Purwadi et al. (2019, 2020), Zglinicki et al. (2021, 2022), and Ngadenin et al. (2023), while Aminuddin et al. (2026) provided stratigraphic context for deep alluvial placers. Al Wafi et al. (2025) was used only as an Indonesian process comparator because its weathered-granite ore was collected in North Sumatra, not Bangka.

For each dataset, the synthesis recorded location, sample medium and number, sampling support, dry-weight basis, analytical method, detection limit when reported, elemental total REE versus oxide-equivalent TREO, inclusion of Y and Ce, host minerals, U-Th information, recovery conditions, spatial resolution, and stated limitations. Elemental values were not converted to

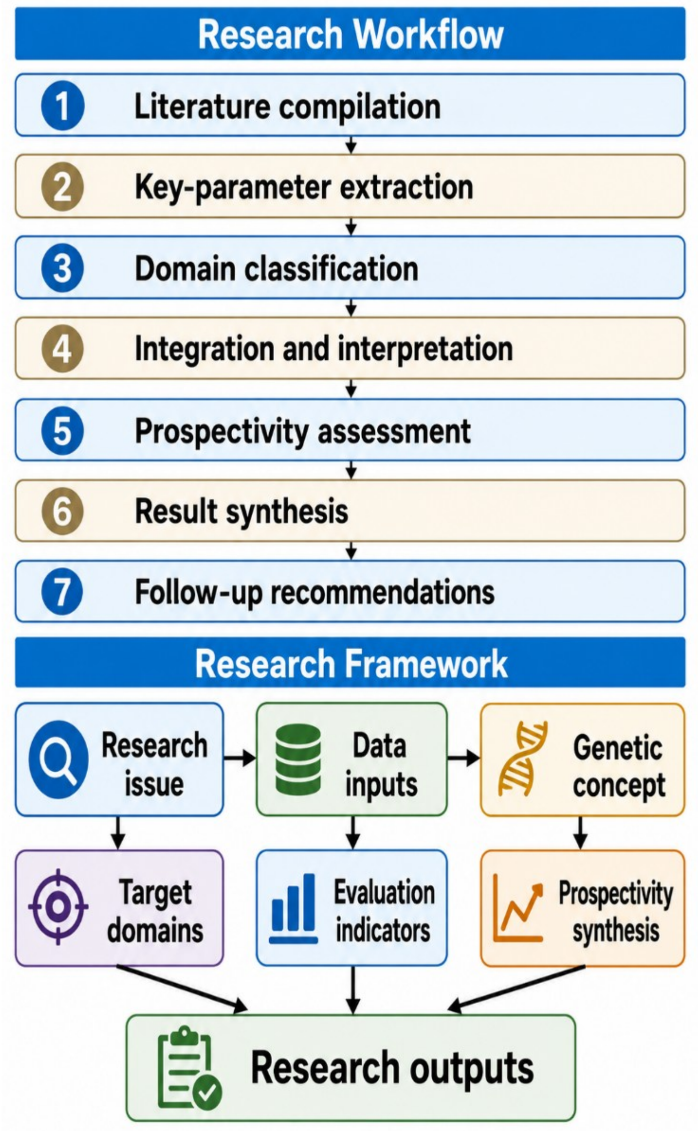

Figure 3. Literature-selection and synthesis workflow used to screen sources, extract comparable evidence, classify domains, and report uncertainty.

oxide equivalents unless the original elemental composition and conversion basis were available. Whole rock, regolith, panned concentrate, mineral separate, placer sediment, tailings, and process residues were compared only within equivalent sample media and analytical bases. Missing or incompatible information was coded as not reported and reduced evidence confidence rather than being replaced by a favorable assumption.

Two independent indices were calculated for each domain. Geological prospectivity was defined as GP = (F + M + C + A)/8, where F is source fertility, M is support for the enrichment mechanism, C is continuity or preservation, and A is accessibility for verification. Evidence confidence was defined as EC = (D + S + V + R)/8, where D is direct mineralogical, geochemical, or leaching evidence; S is sample and spatial support; V is independent or multi-method verification; and R is recovery plus U-Th/NORM characterization. Each component was scored 0 (absent or unsupported), 1 (partial or site-limited), or 2 (direct and supported by multiple observations). Equal weights were used because no empirical calibration supports unequal weighting. GP values of 0.75-1.00 were classified as high, 0.50-0.74 as moderate, and below 0.50 as low; EC values of 0.80-1.00 were high, 0.50-0.79 moderate, and below 0.50 low.

Table 2. Evidence metadata and harmonization rules used in the literature synthesis.

Evidence type	Required metadata	Treatment in synthesis
Regional geology	Map source, scale, CRS, lithology, age, faults/lineaments	Defines source context; structure remains possible influence unless spatially tested
Geochemistry	Sample medium/count, dry basis, method, detection limit, ΣREE/TREO, Y/Ce, Th/U	Compare only like-with-like; flag elemental/oxide or sample-medium incompatibility
Mineralogy	XRD, SEM-EDS, EPMA/MLA, mineral separates, sequential extraction or leaching	Distinguishes mineral-hosted, residual, and exchangeable REE and informs recovery
Geomorphology/ remote sensing	Sensor/date, resolution, indices, DEM, drainage, disturbed-ground and ground truth	Process/land-surface proxy only; not direct REE detection
Preliminary economics	Thickness/grade/recovery/price assumptions, payable factor, U-Th/NORM, costs	Illustrative sensitivity only; not resource, reserve, or project valuation

Sensitivity was tested by changing each uncertain component by one ordinal level while holding the remaining components constant. An exact rank was considered stable only when the domain order did not change; otherwise results were reported as priority tiers. The scoring was applied at domain level and was not interpolated spatially. Direct site-specific measurements were distinguished from process-consistent geological inference and from untested hypotheses. Remote-sensing responses, geomorphic position, and structural lineaments could increase targeting relevance, but could not increase EC above moderate without ground and laboratory verification. Figure 6 is therefore a conceptual screening illustration rather than a weighted GIS output or validated concentration surface (Zhang et al., 2024).

The economic component was restricted to an illustrative gross contained-value sensitivity analysis. Gross contained value was calculated as $GCV = A \times T \times \rho \times (G/1000) \times Rec \times P$, where A is area ($m^2$), T is thickness (m), ρ is bulk density (t/m^3), G is TREO grade (ppm, equivalent to g/t), Rec is assumed recovery, and P is the mixed REO-equivalent price (USD/kg). Thickness, grade, recovery, and price were varied while area and density were held constant. The calculation excludes payable factors, REO basket composition, Th-U penalties, separation and refining losses, CAPEX, OPEX, logistics, taxes, royalties, permitting, rehabilitation, and environmental liability; it is therefore a sensitivity illustration rather than a resource, reserve, project value, or viability assessment.

RESULT AND DISCUSSION

The synthesis distinguishes direct evidence, process-consistent inference, and untested hypothesis. Direct evidence comprises site-specific mineralogical, geochemical, leaching, or radiological measurements. Process-consistent inference links those measurements to established weathering, transport, or processing mechanisms. Untested hypotheses identify proposed controls that still require spatially controlled sampling or experimental verification. This hierarchy allows the same domain to have high geological prospectivity but only moderate confidence.

Source and mineral-host evidence is comparatively strong. Ng et al. (2017) constrained the Bangka granitoids as a Late Triassic continuation of the Main Range province, establishing a defensible magmatic source context. Syafrizal et al. (2024) examined 51 samples spanning primary deposits, placers, concentrates, and tailings and identified monazite and xenotime using microscopy, XRD, SEM, EPMA, and ICP-MS. Their data demonstrate that monazite is principally Ce-rich and carries LREEs such as La and Nd, whereas xenotime is Y-dominant and contains HREEs including Dy and Yb. These observations support mineral-specific exploration and processing decisions, but they do not establish uniform grade or continuity across the province.

Fresh and altered granite domain - The Bangka granitoids provide the primary source framework, and accessory monazite, xenotime, and related phases are directly documented (Ng et al., 2017; Syafrizal et al., 2024). Fresh-rock exploration is nevertheless a longer-horizon target because economic relevance depends on mineral abundance, grain size, liberation, alteration distribution, and continuity. The mapped structures in Figure 1 are regionally informative, but no South Bangka sample-to-fault distance test, orientation analysis, or fracture-density model was available; structural control is therefore retained as a testable influence rather than a scored causal predictor.

Weathered-granite domain - Tampubolon et al. (2024) documented increasing total REE concentrations from horizon B to horizon C at both Toboali (156-188 to 196-268 ppm) and Air Gegas (230-330 to 342-450 ppm) using complementary geochemical and mineralogical methods. Their leaching results support a role for kaolinite in ion adsorption at Air Gegas, whereas resistant monazite and xenotime remain important residual hosts. Agung et al. (2024) independently reported mineralogical and geochemical features consistent with possible ion-adsorption-type enrichment in the Toboali weathered crust. Septiarani et al. (2026) composited samples from five Keposang-Toboali locations; quantitative mineralogy indicated 35.0% quartz, 32.2% kaolinite, 18.4% sanidine, and 9.5% illite, and sulfuric-acid diagnostic leaching recovered approximately 92% of total REEs at 90 °C under high acid dosage. This result demonstrates acid-extractable REEs, but the severe conditions do not by themselves demonstrate low-reagent ion-exchange recovery. The contrast with Al Wafi et al. (2025), who found conventional ammonium-sulfate leaching ineffective for a North Sumatran weathered-granite ore, further shows that the ion-exchangeable fraction and recovery route are deposit specific.

Placer and alluvial domain - Syafrizal et al. (2024) directly documented monazite- and xenotime-bearing placer and concentrate materials, while Ngadenin et al. (2023) demonstrated that monazite and zircon distribution is accompanied by measurable radiological variability in Bangka placer settings. Aminuddin et al. (2026) showed that South Bangka alluvium is vertically differentiated, supporting separate sampling of sandy, clay-rich, gravelly, and basal heavy-mineral intervals. Prospectivity therefore depends on paleochannel geometry, hydraulic sorting, grain-size partitioning, and stratigraphic position rather than on a uniform surface concentration. Required verification comprises stratified auger or pit sampling, heavy-mineral separation, modal mineralogy, grain-size analysis, and U-Th measurement.

Tin-tailings and processing-residue domain - Purwadi et al. (2019) combined ICP-OES, XRD, and reflectance spectroscopy at two abandoned Bangka tailings sites and reported strongly variable Er concentrations (111.6-3768.4 µg/g), illustrating both enrichment potential and severe sample heterogeneity. Purwadi et al. (2020) subsequently showed that Sentinel-2 data can help delineate tailings-related surface materials, but the spectral response is a targeting proxy and not a direct REE assay. Zglinicki et al. (2021, 2022) confirmed that post-processing residues may contain monazite, xenotime, HREEs, and U, while Ngadenin et al. (2023) reinforced the need for radiological characterization. Consequently, accessibility and previous physical concentration improve prospectivity, whereas heap heterogeneity, mineral locking, ownership and liability, beneficiation response, and NORM keep confidence at a moderate level.

Figure 4 is a literature-based genetic model linking primary source minerals, alteration, tropical weathering, slope-drainage transport, placer concentration, and tailings reworking. The sequence is a process synthesis; it does not establish that every mechanism occurs at every location or that ion adsorption is present without diagnostic leaching or mineral-deportment evidence.

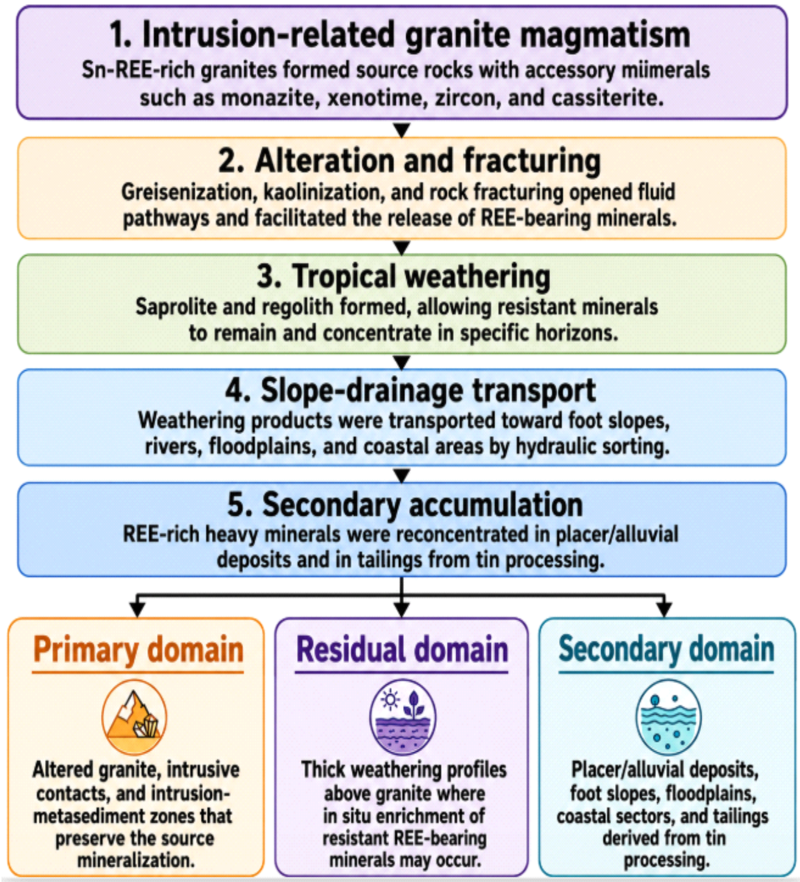

Figure 4. Genetic model of REE enrichment in the Bangka Belitung tin-granite system. Source: modified from Geological Agency (2022), Tampubolon et al. (2024), Syafrizal et al. (2024), and Zglinicki et al. (2022).

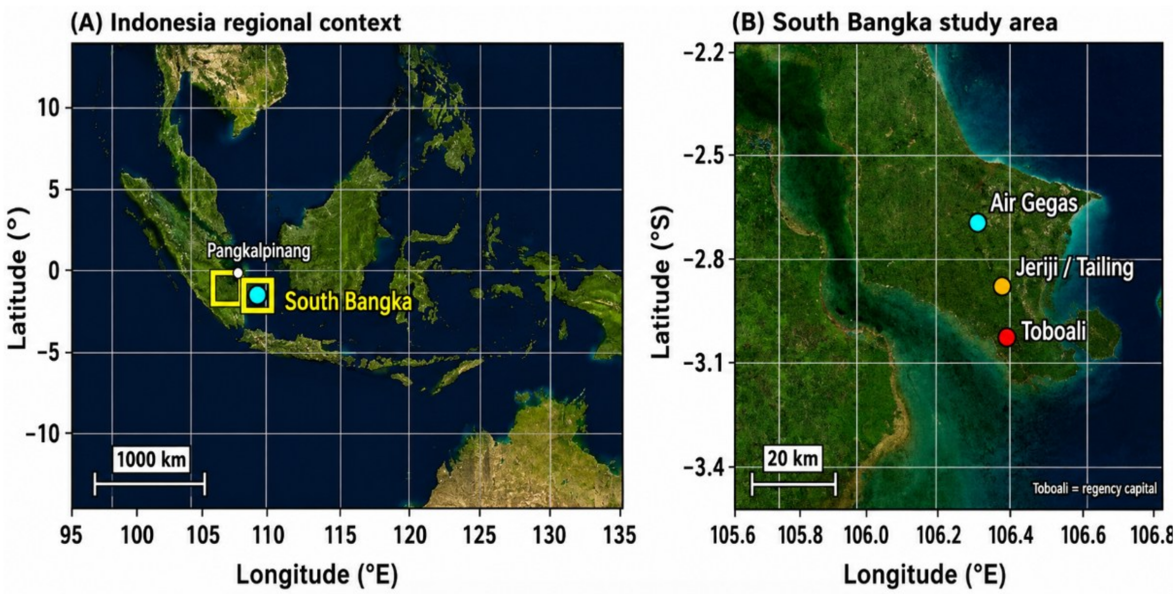

Figure 5. Study-location map showing the regional Indonesian context and the South Bangka study area.

Figure 5 provides regional and South Bangka location context for the areas most frequently discussed in the retained literature, including Air Gegas, Toboali, and Jeriji or nearby residue sectors. The map supports geographic orientation only; target confidence is assigned from the

Table 3. Evidence-confidence rules for qualitative target screening; no weighted GIS model was applied.

Evidence category	Minimum evidence requirement	Confidence treatment
Direct mineral/chemical evidence	Site-specific mineralogy, geochemistry, deportment, or diagnostic leaching	High for the measured property only; do not extrapolate without continuity
Analytical comparability	Same sample medium, basis, method, Y/Ce definition, detection treatment, and support	Otherwise qualitative and explicitly flagged as non-comparable
Geological continuity	Repeated profiles/samples tied to mapped lithology, regolith, or stratigraphy	Moderate-high depending coverage; isolated samples remain local evidence
Spatial proxy	DEM, drainage, Sentinel/Landsat, lineaments, disturbed ground	Supports targeting only; never direct REE concentration or mineral-host proof
Metallurgical and NORM uncertainty	Recovery tests, product composition, U-Th/radiometry, waste and liability data	Confidence is reduced where recovery, representativity, or NORM data are absent
Missing data	Unreported or incompatible data	Record as unknown; never substitute zero or an assumed favorable score

Table 4. Four-domain host-process-test-recovery-risk comparison and evidence confidence

Domain	REE host / process	Diagnostic evidence	Recovery route, key risk, and confidence
Weathered granite: Air Gegas-Toboali	Residual minerals; possible clay/Fe-Mn adsorption	Profile sampling; XRD/SEM-EDS/EPMA; sequential extraction or ion-exchange leach	Mineral separation or selective leach; continuity and U-Th risk; moderate confidence
Tin tailings / processing residues	Monazite/xenotime residues; anthropogenic concentration	Representative composites; grain size; mineral liberation; ICP-MS; radiometry	Physical separation plus hydrometallurgy; heterogeneity/NORM/liability; moderate confidence
Placer / alluvium	Monazite/xenotime/zircon; hydraulic sorting	Stratified pitting/auger; grain size; heavy-mineral separation; U-Th	Physical concentration and separation; strong heterogeneity; moderate confidence
Fresh / altered granite	Accessory monazite/xenotime and related REE minerals; primary hosted	Mapping; petrography; whole-rock and mineral separates; XRD/SEM-EDS/EPMA	Comminution/beneficiation/hydrometallurgy; higher intensity; moderate source confidence

Table 5. Key literature evidence, evidence status, and interpretive limitation.

Author(s)	Evidence status	Supported finding	Use and limitation
Ng et al. (2017)	Direct regional evidence	Late Triassic Main Range source context	Regional context; not site-scale grade or recovery
Tampubolon et al. (2024)	Direct site evidence	Selected South Bangka profiles are enriched	Supports verification; continuity remains uncertain
Agung et al. (2024)	Direct mineralogical evidence	Residual minerals and local clay/Fe-Mn association	Ion adsorption still requires diagnostic leaching
Syafrizal et al. (2024)	Direct mineralogical evidence	Monazite carries LREE; xenotime carries Y/HREE	Host identification does not establish recovery
Purwadi et al. (2020)	Proxy-supported interpretation	Disturbed ground/tailings footprints can be mapped	Remote sensing does not directly measure REE
Zglinicki et al. (2021; 2022)	Direct geochemical/radiological evidence	Residues may contain HREEs, U and Th; NORM varies	Requires representative sampling and recovery tests

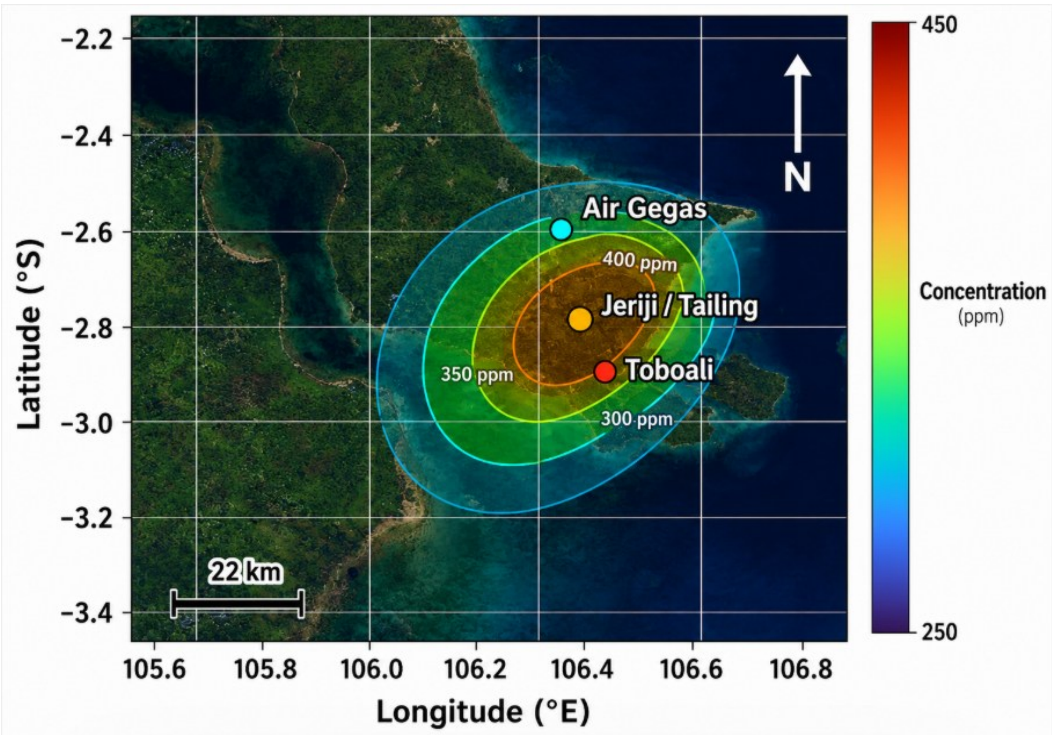

Figure 6. Literature-based conceptual target-screening illustration. Colored zones and ppm labels are schematic markers, not an interpolated geochemical surface or validated prospectivity map.

underlying studies, not from proximity to a plotted point. Figure 6 is retained as a conceptual target-screening illustration. It is not an interpolated geochemical surface, a weighted GIS model, or a validated mineral prospectivity map. The colored zones and ppm labels should be read only as schematic literature markers that indicate where field verification has been discussed. Remote-sensing or geomorphological layers in such screening are process proxies and cannot directly detect REE concentration. Application of the ordinal matrix yielded GP/EC values of 0.88/0.75 for weathered granite, 0.75/0.63 for tin-processing residues, 0.63/0.63 for placer/alluvium, and 0.50/0.50 for fresh or altered granite. Weathered granite therefore occupies the highest geological-priority tier, but its confidence remains moderate because continuity, recovery selectivity, and radiological coverage are incomplete. One-level sensitivity perturbations preserved weathered granite within the top tier but did not produce a robust separation from tailings under all adverse assumptions; exact ranking beyond priority tiers is therefore not claimed. Air Gegas and Toboali are interpreted as priority verification areas within the weathered-granite domain, not as independently validated resources or economic targets.

Table 4 compares the four domains by host, enrichment process, diagnostic tests, recovery route, principal limitation, and evidence confidence. Table 5 identifies which conclusions are direct evidence, literature-based inference, or proxy-supported interpretation. Together, the tables prevent a single bulk grade or remote-sensing response from being treated as a validated prospectivity result. The combined evidence supports a linked source-weathering-transport-processing system and clarifies why apparently similar REE concentrations may represent different exploration and processing problems. The principal advance is the explicit separation of material domain, enrichment mechanism, analytical comparability, geological prospectivity, evidence confidence, extractability, and NORM risk. This structure makes the synthesis auditable and prevents high bulk concentration, favorable spectral response, or near-surface access from being treated as interchangeable evidence of an economically recoverable target.

The sensitivity analysis in Table 6 illustrates the dominance of uncertain assumptions. With a fixed conceptual area of 1 km^2 and density of 1.8 t/m^3, the tested ranges of thickness (2-8 m), TREO grade (200-600 ppm), recovery (30-70%), and mixed REO-equivalent price (USD 8-20/kg) generate a broad gross contained-value envelope. The former USD 35.1 million case is only one interior scenario. Because no payable factor, REO basket, Th-U penalty, separation cost, CAPEX/OPEX, tax, or environmental liability is included, the calculation is useful only for identifying which variables require measurement before economic screening can proceed.

CONCLUSION

The Bangka Belitung REE system is most effectively assessed through four material domains - fresh or altered granite, weathered granite, placer/alluvium, and tin-processing residues - because each domain contains different mineral hosts, enrichment mechanisms, recovery routes, and environmental constraints. The evidence-constrained matrix identifies weathered granite as the leading geological-priority tier, while retaining only moderate confidence because continuity, selective recovery, and U-Th/NORM coverage remain incomplete.

The strongest direct evidence comprises Late Triassic granitic source rocks; monazite as a Ce-rich LREE host; xenotime as a Y-HREE host; lower-horizon enrichment at Toboali and Air Gegas; and acid-extractable REEs in the Keposang-Toboali weathered material. These results support Air Gegas and Toboali as priority verification areas, but they do not demonstrate province-scale continuity or uniform ion-exchange behavior. Tailings and placers remain credible near-surface targets, although their heterogeneity, mineral locking, and NORM liabilities require explicit characterization. Remote sensing and structural interpretation are useful for targeting only when tied to ground data.

The next decision-critical work is a spatially controlled program of regolith drilling or auger sampling, stratified placer and tailings sampling, harmonized ICP-MS or ICP-OES analysis, XRD and SEM-EDS/EPMA or MLA-based mineral deportment, mild-salt and sequential leaching, beneficiation testing, and U-Th radiometry. These data are required to distinguish residual mineral grains from genuinely exchangeable REEs, quantify continuity and recovery, define product quality and liabilities, and determine whether any target warrants resource definition or technoeconomic evaluation. The gross contained-value calculation should remain a sensitivity tool until these uncertainties are resolved.

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DECLARATIONS

Author contributions

A.R.: conceptualization, methodology, evidence synthesis, visualization, and writing - original draft. E.S.: validation, supervision, and writing - review and editing. R.A.E.W.: geological interpretation, validation, and writing - review and editing. All authors reviewed and approved the final manuscript.

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None.

The use of AI-assisted technologies

None.

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbol	Definition	Unit
REE	Rare earth elements	-
LREE	Light rare earth elements	-
HREE	Heavy rare earth elements	-
TREO	Total rare earth oxides	ppm or %
REO	Rare earth oxide product equivalent	kg or USD/kg
ICP-MS	Inductively coupled plasma mass spectrometry	-
SEM-EDS	Scanning electron microscopy with energy-dispersive spectroscopy	-
XRD	X-ray diffraction	-
ΣREE	Sum of reported rare earth elements on an elemental basis	ppm or %
NORM	Naturally occurring radioactive material	-
CRS	Coordinate reference system	-

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