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Integrated Geophysical and Reactive Transport Assessment of Fracture-Controlled Rare Earth Mineral Recovery in Pegmatitic Subsurface Systems

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Abstract

The increasing global demand for rare earth elements (REEs) for clean energy technologies, advanced electronics, and sustainable industrial applications has intensified the need for efficient and environmentally responsible subsurface mineral recovery strategies. This study presents an integrated hydrogeophysical and reactive transport modelling framework for evaluating fracture-controlled rare earth element recovery within pegmatitic subsurface systems. The approach combines electrical resistivity tomography (ERT), seismic refraction analysis, petrophysical parameter estimation, mineralogical characterization, and coupled reactive transport simulations to investigate the influence of structural heterogeneity on fluid migration and mineral dissolution behaviour. Integrated geophysical interpretation identified pronounced subsurface variability characterized by low-resistivity conductive fracture corridors ($<200 \Omega\text{m}$) spatially associated with reduced seismic velocities (3.0–4.5 km/s), elevated porosity, and enhanced permeability. Petrophysical transforms derived from Archie's Law, the Wyllie time-average equation, and the Kozeny–Carman relationship revealed permeability distributions ranging approximately from 120 to 480 mD within structurally altered pegmatitic zones, indicating favourable conditions for fracture-assisted reactive fluid transport and mineral dissolution. SEM, SEM-EDS, XRD, and BET analyses confirmed the occurrence of REE-bearing mineral phases including monazite, bastnäsite, xenotime, and zircon within quartz–feldspar-rich pegmatitic matrices. Microstructural observations further revealed interconnected fracture networks

Keywords: Rare earth elements (REEs), Pegmatitic subsurface systems, Electrical resistivity tomography, Reactive transport modelling, Fracture-controlled mineralization, Hydrogeophysical characterization.

1. Introduction

The accelerating global transition toward low-carbon and renewable energy systems has significantly increased the demand for rare earth element (REE)-bearing pegmatitic mineral

systems, which are essential components in batteries, electric vehicles, wind turbines, and other clean energy technologies [1], [2]. These minerals are central to achieving global climate targets and ensuring energy security; however, their supply chains are increasingly constrained by declining ore grades, geopolitical dependencies, and the environmental impacts associated with conventional mining practices [3], [4]. Traditional extraction methods, including open-pit and underground mining, are often energy-intensive and environmentally disruptive, contributing to land degradation, groundwater contamination, and greenhouse gas emissions [5]. Consequently, there is a growing need for alternative extraction strategies that are both efficient and environmentally sustainable, particularly those capable of accessing resources in subsurface environments without extensive surface disturbance. In this context, subsurface-based extraction approaches such as in-situ recovery (ISR) and fluid-assisted leaching have emerged as promising alternatives, offering the potential to extract minerals directly from geological formations while minimizing surface impact [6]. The effectiveness of such approaches, however, is strongly dependent on the physical and structural properties of the subsurface, including lithology, porosity, permeability, and the presence of fractures and fluid pathways that facilitate reagent transport and mineral dissolution. Accurate characterization of these subsurface features is therefore critical for identifying zones with high extraction potential and for optimizing recovery processes. Geophysical methods provide powerful tools for imaging and characterizing subsurface systems, enabling the identification of structural heterogeneities and mineralized zones that are not accessible through direct observation. Seismic techniques, for instance, offer insights into the elastic properties and mechanical behavior of rocks, with seismic velocity variations reflecting changes in lithology, density, and fracture distribution [7]. Electrical resistivity methods, on the other hand, are highly sensitive to fluid content, porosity, and mineralization, making them particularly effective for detecting conductive zones associated with fluid-rich and potentially mineral-bearing formations [8]. When applied in combination, these methods provide complementary information that enhances the resolution and reliability of subsurface characterization. Previous studies have shown that low-resistivity anomalies are often associated with zones of increased porosity and fluid saturation, which are critical for facilitating fluid flow and enhancing the efficiency of in-situ leaching processes [9], [10]. Similarly, reduced seismic velocities have been linked to fractured and mechanically generated formations that may serve as conduits for fluid movement and mineral mobilization [11]. These geophysical indicators are therefore valuable for identifying subsurface environments that are conducive to mineral recovery. However, despite their effectiveness in delineating subsurface structures, geophysical methods are inherently limited in their ability to directly quantify extraction performance or predict recovery efficiency under varying operational conditions. Concurrently, advances in chemical engineering and process metallurgy have led to the development of sophisticated extraction techniques capable of recovering metals from complex and low-grade deposits. Hydrometallurgical processes, including acid leaching, solvent extraction, and electrochemical recovery, have proven particularly effective due to their adaptability and relatively lower environmental footprint compared to pyrometallurgical methods [12], [13]. The efficiency of these processes is governed by a range of operational parameters, including temperature, reagent concentration, reaction kinetics, and mass transfer within porous media [14]. Optimizing these parameters is essential for maximizing recovery while minimizing costs and environmental impacts. However, process optimization is often conducted under simplified or laboratory-controlled conditions that do not fully account for the heterogeneity and complexity of natural subsurface systems. A critical limitation in current research is the lack of

integration between geophysical characterization and process-based modelling. Most studies treat these domains independently, with geophysical investigations focusing on mapping subsurface features and process engineering studies emphasizing extraction efficiency without incorporating realistic geological constraints [15]. This separation creates a significant gap in the ability to link subsurface properties with extraction performance, resulting in uncertainties in resource evaluation and limiting the effectiveness of extraction strategies. Furthermore, existing integrated approaches are often qualitative in nature, lacking the quantitative coupling required to establish direct relationships between geophysical parameters and recovery outcomes [16]. As a result, the potential of geophysical data to inform and optimize extraction processes remains underutilized. Another important challenge lies in the inadequate representation of subsurface heterogeneity in process models. Many conventional models assume homogeneous conditions, neglecting spatial variations in lithology, porosity, and fracture networks that significantly influence fluid flow, reagent transport, and reaction kinetics [17]. This simplification can lead to inaccurate predictions of recovery efficiency and may result in suboptimal design and operation of extraction systems. Additionally, the increasing emphasis on sustainable resource development requires approaches that not only improve recovery efficiency but also reduce environmental impact through targeted extraction and optimized resource utilization [18]. Achieving this objective necessitates a comprehensive framework that integrates high-resolution subsurface characterization with process-based modelling in a quantitative and systematic manner. Against this backdrop, a clear research problem emerges in the form of the absence of a unified and quantitatively coupled framework that links geophysical indicators of subsurface conditions with process-based metrics of mineral recovery efficiency. The inability to directly translate geophysical observations into actionable process parameters limits the predictive capability of current models and constrains the development of efficient and sustainable extraction strategies. Addressing this problem requires an approach that bridges the gap between subsurface imaging and process engineering by establishing explicit relationships between geophysical properties and extraction performance. This study responds to this need by developing an integrated geophysical–process modelling framework that quantitatively links seismic velocity and electrical resistivity with hydrometallurgical recovery efficiency in subsurface systems. By incorporating subsurface heterogeneity into process simulations and introducing an integrated recovery potential index that combines geophysical and process parameters, the study provides a novel approach for evaluating and optimizing critical mineral extraction. The framework not only enhances the accuracy of resource assessment but also enables targeted extraction strategies that improve recovery efficiency and reduce environmental impact. In doing so, this work advances the current state of knowledge by demonstrating how the coupling of geophysical data with process engineering principles can be used to develop scalable and sustainable solutions for critical mineral recovery in support of the global energy transition.

1.1 Study Area and Geological Setting

Location and Accessibility

The study area is located within the Nasarawa–Keffi pegmatite belt in north-central Nigeria, a region recognized for structurally controlled pegmatitic intrusions associated with rare earth element (REE)-bearing mineralization. The area lies within the Nigerian Basement Complex and is geographically positioned between latitudes 8°15'N and 8°45'N and longitudes 7°45'E and

8°30'E, encompassing parts of Nasarawa State and adjoining tectonic blocks. Accessibility to the study area is provided by major highways connecting Keffi, Akwanga, Nasarawa Eggon, and Lafia, complemented by secondary road networks and local mining tracks that extend into pegmatite-rich outcrops. These access routes facilitate geological mapping, geophysical surveying, and subsurface sampling across both exposed and partially weathered terrains. The topography of the area is generally undulating, characterized by low ridges, weathered basement exposures, and scattered granitic outcrops. Elevation ranges from approximately 250 m to 620 m above sea level. The region experiences a tropical sub-humid climate with distinct wet and dry seasons, annual rainfall between 1200 mm and 1600 mm, and average temperatures ranging from 24°C to 34°C. These climatic conditions contribute to significant chemical weathering, which influences near-surface alteration, regolith development, and groundwater recharge processes.

Regional Geological Setting

The study area forms part of the Precambrian Nigerian Basement Complex, which consists predominantly of migmatite–gneiss complexes, schist belts, and Older Granites emplaced during the Pan-African orogeny (~600 Ma). The tectonic evolution of this basement terrain is associated with intense deformation, metamorphism, and widespread granitic and pegmatitic intrusions. Lithologically, the region is composed of migmatitic gneisses, biotite- and hornblende-bearing granites, quartzites, amphibolites, and schistose sequences that have undergone multiple phases of deformation. These basement rocks are intruded by coarse-grained pegmatitic bodies that occur as dykes, veins, and lenses of varying thickness and lateral continuity. The pegmatites are predominantly enriched in quartz, feldspar, and mica, with accessory and locally concentrated rare earth element (REE)-bearing minerals including monazite, bastnäsite, xenotime, and zircon. Their emplacement is structurally controlled, occurring preferentially along zones of weakness such as fractures, shear zones, and regional fault intersections. Regional structural trends are dominated by NE–SW and NW–SE orientations, reflecting Pan-African tectonic stress regimes. These structural fabrics strongly influence the spatial distribution of pegmatitic intrusions and associated mineralization. The interplay between lithology and deformation has resulted in a heterogeneous basement architecture that governs subsurface fluid migration and mineral deposition patterns.

Structural Framework and Mineralization

The structural framework of the study area is defined by a dense network of fractures, faults, and shear zones that control the emplacement and geometry of pegmatitic bodies. These structural discontinuities exhibit predominant NE–SW and subordinate NW–SE orientations, consistent with regional tectonic trends across the Nigerian Basement Complex. Fracture systems play a critical role in controlling subsurface permeability and fluid flow pathways. Interconnected fracture networks facilitate hydrothermal fluid circulation, which contributes to the concentration and redistribution of rare earth element (REE) mineralization within pegmatitic zones. In contrast, isolated or poorly connected fractures exhibit limited fluid transmissivity and reduced mineralization potential. Pegmatite emplacement is strongly associated with these structural discontinuities, where dilational zones provide space for magma intrusion and subsequent crystallization. The resulting pegmatitic bodies are commonly elongated along fracture trends, indicating syn-tectonic emplacement conditions. Mineralization within these structural zones is

characterized by localized enrichment of REE-bearing minerals such as monazite, bastnäsite, and xenotime. These minerals are typically disseminated within feldspar-rich matrices or concentrated along micro-fractures and grain boundaries, reflecting fluid-assisted transport and precipitation processes. The structural heterogeneity of the host rocks therefore exerts a primary control on both mineral distribution and potential recovery efficiency.

Hydrogeological Characteristics

The hydrogeological regime of the study area is strongly influenced by its crystalline basement composition and associated fracture networks. Groundwater occurrence is predominantly controlled by secondary porosity within weathered zones and fractured bedrock aquifers, as primary porosity is negligible in the crystalline lithologies. The weathered overburden varies in thickness from approximately 5 m to 35 m, depending on lithological composition and structural intensity. Beneath this zone, fractured bedrock constitutes the principal aquifer system, with groundwater flow occurring primarily through interconnected fracture networks and fault zones. Hydraulic conductivity within the fractured basement is highly heterogeneous, reflecting variations in fracture density, aperture, and connectivity. Zones of enhanced fracturing exhibit higher permeability and serve as preferential pathways for fluid migration. These characteristics are critical for fluid-assisted mineral recovery processes, as they directly influence reagent transport, reaction front propagation, and dissolution efficiency. Seasonal recharge from precipitation significantly impacts groundwater levels and subsurface fluid dynamics, particularly during the wet season. This temporal variability plays an important role in modulating fluid-rock interaction processes within the fracture-controlled system.

Target Critical Minerals

The primary target mineralization within the study area consists of rare earth element (REE)-bearing pegmatitic systems hosted within granitic and pegmatitic intrusions. The economically significant minerals include monazite, bastnäsite, xenotime, and zircon, which occur as accessory phases within feldspar- and quartz-dominated pegmatites. Monazite and bastnäsite represent the principal REE-bearing phases and are commonly associated with late-stage hydrothermal alteration and fluid-assisted mineral deposition. These minerals occur either as disseminated grains within the pegmatitic matrix or concentrated along fractures and grain boundaries, where fluid pathways enhance elemental mobility and precipitation. The spatial distribution of REE mineralization is strongly controlled by structural features, particularly fracture intersections and shear zones that act as conduits for mineralizing fluids. This structural control results in localized enrichment zones that are highly relevant for subsurface extraction and reactive transport modelling. The selection of this mineral system provides a realistic geological framework for evaluating the integration of geophysical characterization and reactive transport simulation in predicting fracture-controlled mineral recovery efficiency within pegmatitic environments.

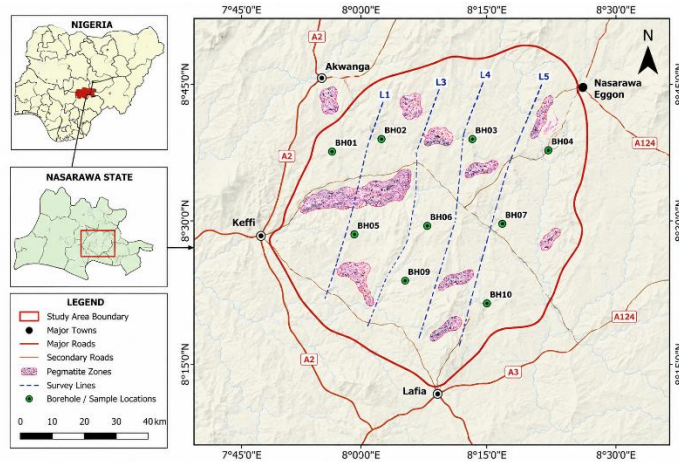


Figure 1: Location and Accessibility Map of the Study Area

2. Materials and Methods

This study employed a multidisciplinary approach integrating geophysical simulations, laboratory mineralogical characterization, and process-based modelling to evaluate critical mineral recovery from subsurface systems for sustainable energy technologies. The methodology ensures that simulated geophysical parameters are anchored with real mineralogical evidence, maximizing reliability and predictive power.

Study Framework

A combined modelling framework was implemented, linking subsurface geophysical characterization with reactive transport and process-based simulations. The framework includes three key components: geophysical modelling to define subsurface structure and fracture networks, laboratory mineralogical analyses to quantify surface area, porosity, and mineral phases, and process-based reactive transport modelling to simulate dissolution and recovery dynamics. The integration of these components enables identification of optimal zones for mineral recovery while quantifying environmental and operational efficiencies.

Geophysical Survey Design

Integrated geophysical investigations were conducted across structurally controlled pegmatite-hosting zones within the Nasarawa–Keffi pegmatite belt to characterize subsurface heterogeneity, fracture connectivity, and fluid migration pathways associated with rare earth element (REE)-bearing mineralization. The survey design incorporated electrical resistivity tomography (ERT) and seismic refraction methods to obtain complementary information on lithological variability, fracture distribution, porosity, and subsurface mechanical properties. Geophysical traverses were strategically oriented perpendicular to the dominant NE–SW regional structural trend in order to maximize imaging resolution across fracture-controlled pegmatitic intrusions. Five survey profiles were established across zones identified from geological mapping, surface lineament analysis, and exposed pegmatitic outcrops. Individual profile lengths ranged from approximately 200 m to 500 m depending on terrain accessibility and

structural continuity. Survey locations were selected based on the occurrence of mapped fracture systems, hydrothermal alteration signatures, and localized mineralized zones interpreted from field observations and structural analysis. Additional considerations included topographic stability, overburden thickness, and accessibility for integrated geophysical acquisition. The combined geophysical approach enabled correlation between electrical resistivity anomalies, seismic velocity contrasts, and structurally controlled subsurface features. This integration reduced interpretation uncertainty and provided improved characterization of fracture-controlled flow pathways and lithological heterogeneity relevant to reactive transport modelling. Borehole and sample locations were positioned along selected traverses to facilitate lithological calibration, mineralogical analysis, and validation of interpreted subsurface structures. These control points were subsequently used to constrain porosity estimation, permeability distribution, and fracture-network characterization within the reactive transport framework.

Electrical Resistivity Tomography

Electrical resistivity tomography (ERT) surveys were conducted to characterize subsurface lithological variability, fracture distribution, and fluid migration pathways within the pegmatite-hosting formations. The method was selected due to its sensitivity to variations in porosity, fluid saturation, weathering intensity, and fracture connectivity, which are critical parameters influencing reactive fluid transport and mineral dissolution processes. Data acquisition was performed using a multi-electrode resistivity imaging system configured in a Wenner–Schlumberger array due to its balanced sensitivity to both vertical and lateral resistivity variations. Electrode spacing was maintained at 5 m along each survey traverse, providing an effective compromise between depth penetration and near-surface resolution. Survey profile lengths ranged between 200 m and 500 m depending on terrain accessibility and structural continuity within the mapped pegmatitic zones. The ERT profiles were oriented approximately perpendicular to the dominant regional fracture trend to maximize imaging resolution across structurally controlled subsurface features. Stainless steel electrodes were implanted along prepared traverses to ensure stable ground contact and minimize contact resistance during acquisition. Data quality control procedures included repeat measurements, removal of noisy readings, and verification of electrode continuity prior to inversion processing. Measured apparent resistivity values ranged approximately between 50 Ωm and 1000 Ωm , reflecting significant subsurface heterogeneity associated with weathered overburden, fractured basement zones, fluid-saturated pathways, and relatively competent pegmatitic intrusions. Low-resistivity anomalies were interpreted as zones of enhanced fluid saturation and interconnected fractures, whereas high-resistivity regions were associated with relatively unfractured granitic and pegmatitic bodies. Two-dimensional inversion of the apparent resistivity data was performed using a smoothness-constrained least-squares inversion algorithm implemented within RES2DINV software. The inversion process iteratively minimized the root mean square (RMS) error between observed and calculated apparent resistivity values until convergence was achieved. Final RMS errors were maintained below 5%, indicating acceptable inversion reliability and data consistency. The resulting resistivity models were subsequently integrated with seismic velocity information and structural interpretations to constrain permeability distribution, fracture connectivity, and fluid migration pathways within the reactive transport modelling framework.

Seismic Refraction Survey

Seismic refraction surveys were conducted to characterize subsurface mechanical properties, lithological boundaries, weathered overburden thickness, and fracture-controlled basement structures within the pegmatitic formations. The method was integrated with electrical resistivity tomography to improve subsurface interpretation reliability and constrain structural features influencing fluid migration and reactive transport processes. Data acquisition was performed using a multi-channel seismic system equipped with 14 Hz vertical geophones distributed along the survey traverses. Geophone spacing was maintained at 5 m intervals to provide adequate resolution of shallow and intermediate subsurface structures. Seismic energy was generated using a sledgehammer source striking a steel plate positioned at designated shot points along each profile. Forward and reverse shooting geometries were implemented to improve travel-time coverage and minimize directional bias during velocity interpretation. Additional intermediate shot points were acquired where necessary to enhance imaging continuity across structurally heterogeneous zones. Survey profiles were aligned approximately perpendicular to the dominant fracture orientation to maximize sensitivity to subsurface discontinuities and fractured basement zones. First-arrival travel times were manually picked and processed to generate subsurface P-wave velocity models. Velocity inversion was performed using tomographic inversion algorithms to obtain two-dimensional seismic velocity distributions along each traverse. The inversion procedure iteratively minimized travel-time residuals between observed and calculated seismic arrivals until stable convergence was achieved. The resulting seismic velocity models revealed velocity variations ranging approximately from 3.0 km/s to 6.0 km/s across the study area. Lower seismic velocities were interpreted as weathered, fractured, or fluid-saturated zones characterized by enhanced porosity and reduced mechanical competence. In contrast, higher seismic velocities corresponded to relatively competent granitic and pegmatitic basement units with lower fracture density and reduced fluid transmissivity. Integration of seismic velocity distributions with resistivity anomalies enabled improved delineation of fracture-controlled flow pathways, weathered basement interfaces, and structurally altered zones relevant to fluid-assisted rare earth mineral recovery. The combined geophysical interpretation also provided essential constraints for permeability estimation and reactive transport simulations.

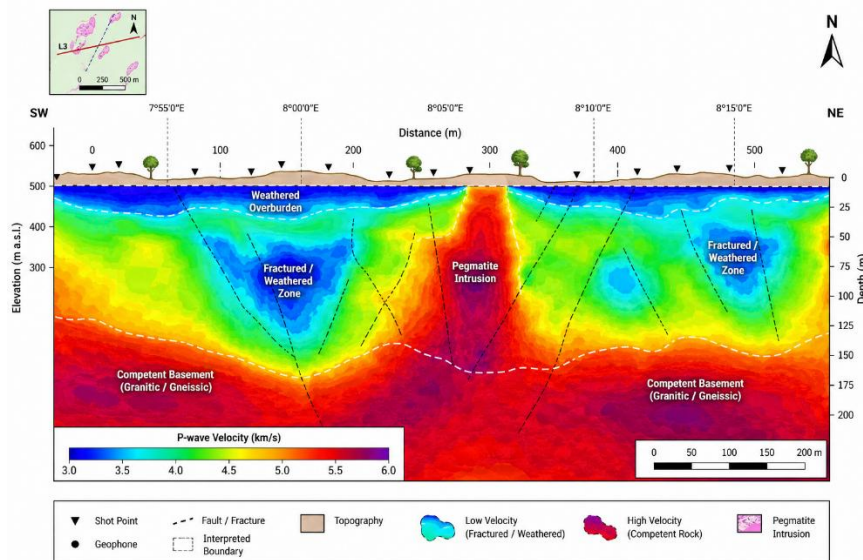


Figure 2: Representative seismic velocity tomography section showing subsurface velocity distribution, fractured basement zones, weathered overburden, and structurally controlled pegmatitic intrusions within the study area.

Geophysical Data Processing and Inversion

Acquired geophysical datasets were processed using standardized filtering, inversion, and interpretation workflows to improve data reliability and reduce acquisition-related noise prior to integration within the reactive transport modelling framework. Processing procedures were designed to preserve subsurface structural signatures while minimizing artefacts associated with electrode contact resistance, signal attenuation, environmental interference, and travel-time picking uncertainty. For the electrical resistivity tomography (ERT) datasets, preliminary quality assessment involved removal of anomalous measurements exhibiting excessively high contact resistance or unstable signal responses. Apparent resistivity datasets were subsequently filtered to suppress outlier values and improve inversion stability. Two-dimensional inversion was performed using a smoothness-constrained least-squares inversion algorithm implemented in RES2DINV software. The inversion procedure iteratively minimized discrepancies between observed and calculated apparent resistivity values while maintaining geologically realistic subsurface resistivity gradients. Topographic corrections were incorporated during inversion to account for elevation variability along the survey traverses. Model refinement continued until stable convergence was achieved, with final root mean square (RMS) errors generally maintained below 5%. The resulting resistivity sections were interpreted in terms of lithological variability, fracture connectivity, weathered overburden thickness, and fluid-saturated structural pathways. Seismic refraction datasets were processed through first-arrival travel-time analysis and tomographic inversion. Manual and semi-automated picking procedures were employed to identify primary seismic arrivals across all shot records. Travel-time datasets were subsequently inverted using iterative tomographic reconstruction algorithms to generate two-dimensional P-wave velocity models. Velocity inversion incorporated forward and reverse shot geometries to improve spatial resolution and minimize directional bias. Residual travel-time errors were progressively minimized through iterative model updates until acceptable convergence between observed and calculated arrival times was obtained. The final velocity models provided quantitative estimates of subsurface mechanical competence, weathering intensity, and fracture-controlled heterogeneity. Integrated interpretation of the resistivity and seismic velocity models enabled improved delineation of fractured basement zones, pegmatitic intrusions, and preferential fluid migration pathways. Low-resistivity and low-velocity anomalies were interpreted as structurally altered or fluid-saturated regions characterized by enhanced porosity and permeability, whereas high-resistivity and high-velocity zones were associated with relatively competent crystalline basement units. To improve interpretation consistency, geophysical anomalies were correlated with borehole lithological information, mineralogical analyses, and mapped structural features. This integration reduced uncertainty in subsurface characterization and provided improved constraints for permeability estimation, fracture-network representation, and subsequent reactive transport simulations.

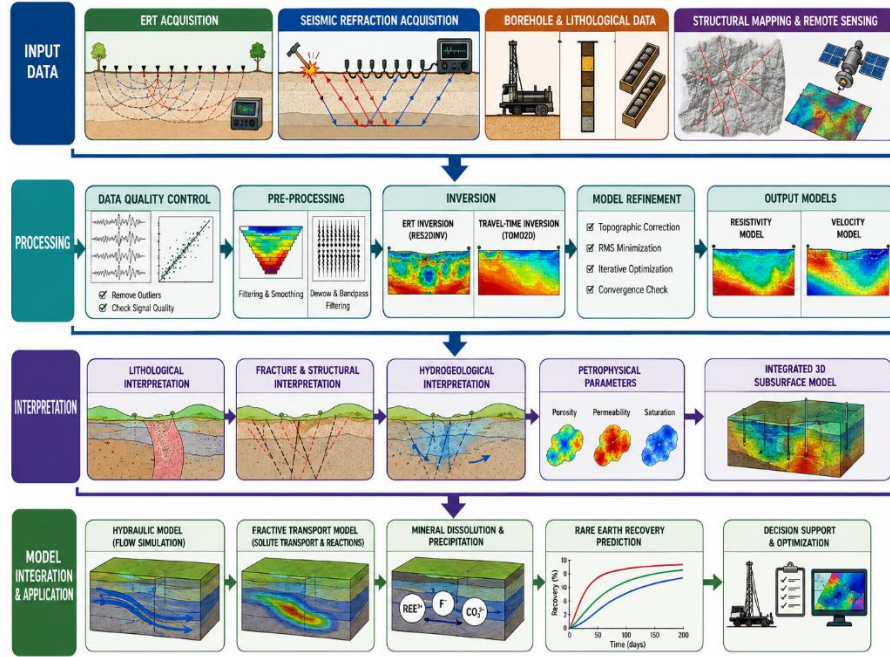


Figure 3: Integrated Geophysical Interpretation Workflow

Petrophysical Parameter Estimation

Petrophysical parameter estimation was conducted to establish quantitative relationships between geophysical measurements and the hydraulic properties required for reactive transport modeling. Electrical resistivity and seismic velocity datasets were integrated with borehole observations and mineralogical analyses to derive spatial distributions of porosity, permeability, fluid saturation, and fracture-controlled hydraulic conductivity within the pegmatitic subsurface system. Porosity estimation from resistivity data was performed using Archie's empirical relationship, which relates bulk resistivity to pore-fluid resistivity and fluid saturation within fractured geological media.

$$\rho = a \rho_w \phi^{-m} S_w^{-n} \quad (i)$$

where ρ is the bulk resistivity of the formation, ρ_w is the pore-fluid resistivity, ϕ is porosity, S_w is water saturation, and a , m , and n represent the tortuosity, cementation, and saturation exponents, respectively. The parameters were calibrated using borehole lithological information and laboratory-derived porosity measurements obtained from representative core samples. Seismic velocity data were used to estimate porosity and subsurface mechanical competence through the Wyllie time-average relationship:

$$\frac{1}{V_p} = \frac{\phi}{V_f} + \frac{1-\phi}{V_m} \quad (ii)$$

where V_p represents the measured compressional wave velocity, V_f is the seismic velocity within pore fluids, V_m is the matrix velocity of the host rock, and ϕ is porosity. Lower seismic velocities were interpreted as fractured or weathered regions characterized by enhanced porosity and reduced mechanical competence. Permeability estimation was subsequently derived using a modified Kozeny–Carman relationship linking porosity to hydraulic conductivity within fractured porous media:

$$k = \frac{\phi^3}{S^2(1 - \phi)^2}$$

(iii)

where k is permeability, ϕ is porosity, and S represents the specific surface area determined from BET adsorption measurements and SEM-based surface characterization. The calculated permeability distributions were further constrained using mapped fracture density and structural connectivity interpreted from integrated geophysical datasets. Hydraulic conductivity distributions derived from the integrated petrophysical workflow were subsequently incorporated into the reactive transport simulations to constrain fluid migration pathways, reaction front propagation, and mineral dissolution behaviour. Zones characterized by low resistivity, reduced seismic velocity, elevated porosity, and enhanced fracture connectivity were interpreted as preferential pathways for reactive fluid transport and mineral recovery. To improve parameter reliability, petrophysical estimates were validated through comparison with borehole observations, laboratory porosity measurements, and mineralogical characterization obtained from SEM and XRD analyses. This integrated workflow minimized uncertainty in hydraulic parameter estimation and improved the predictive capability of the coupled geophysical–reactive transport modelling framework.

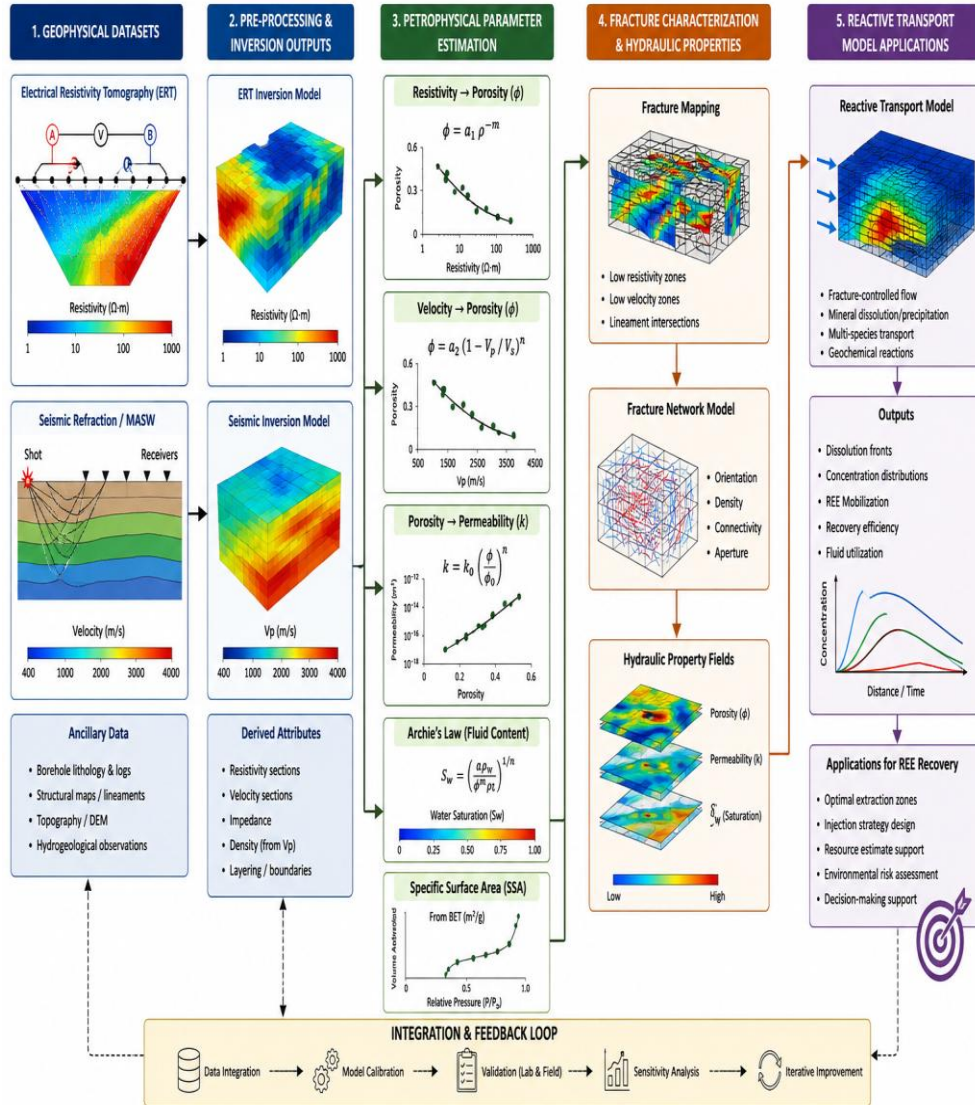


Figure 4: Integrated petrophysical parameter estimation workflow linking geophysical datasets, hydraulic property transforms, fracture characterization, and reactive transport model applications for fracture-controlled rare earth mineral recovery within pegmatitic subsurface systems.

Sample Acquisition and Preparation

Representative subsurface rock and mineral samples were collected from selected boreholes and exposed pegmatitic outcrops across the Nasarawa–Keffi pegmatite belt to characterize lithological variability, fracture-controlled mineralization, and mineralogical composition associated with rare earth element (REE)-bearing systems. Sampling locations were selected along integrated geophysical traverses to facilitate direct correlation between laboratory-derived mineralogical parameters and interpreted subsurface geophysical anomalies. Core samples were obtained from fractured and relatively competent pegmatitic intervals at depths ranging approximately from 50 m to 100 m in order to capture vertical lithological heterogeneity and

structural variability within the subsurface system. Particular emphasis was placed on sampling zones exhibiting visible alteration, fracture concentration, quartz–feldspar enrichment, and suspected REE mineralization. Collected samples were logged, photographed, and classified based on lithology, structural characteristics, fracture intensity, weathering condition, and mineral occurrence prior to laboratory preparation. Representative portions of the samples were subsequently processed for scanning electron microscopy (SEM), X-ray diffraction (XRD), and Brunauer–Emmett–Teller (BET) surface area analysis. For SEM analysis, rock specimens were sectioned, mechanically polished, and coated with a thin conductive gold–palladium layer to minimize charging effects during imaging. The prepared samples were used to investigate fracture morphology, mineral texture, grain-boundary relationships, and the spatial distribution of REE-bearing mineral phases within the pegmatitic matrix. For XRD analysis, representative sample fractions were pulverized into fine homogeneous powders using an agate mortar to minimize contamination and preferred orientation effects. Powdered samples were subsequently analyzed to identify crystalline mineral phases and quantify relative mineral abundances associated with REE-bearing pegmatitic mineralization. Specific surface area and pore-related properties were determined using BET adsorption techniques to constrain reactive surface area estimates required for reactive transport simulations. Laboratory-derived porosity and surface area measurements were subsequently integrated with geophysical interpretations to improve permeability estimation, dissolution kinetics, and fluid–rock interaction modelling within the fracture-controlled subsurface environment.

Laboratory Characterization

Laboratory characterization was conducted to determine the mineralogical composition, microstructural properties, elemental distribution, and reactive surface characteristics of the REE-bearing pegmatitic samples. The analyses were designed to validate geophysical interpretations and provide quantitative parameters required for reactive transport modelling and fracture-controlled mineral recovery simulations.

Scanning Electron Microscopy and Elemental Analysis

Scanning electron microscopy (SEM) was employed to investigate mineral textures, micro-fracture development, grain morphology, alteration features, and pore-scale structural heterogeneity within the pegmatitic samples. Imaging was conducted using accelerating voltages ranging from 10 kV to 20 kV and magnifications between 500× and 5000× depending on the scale of the investigated microstructural features. SEM imaging revealed interconnected micro-fractures, grain-boundary dissolution features, and structurally controlled alteration zones that are critical for fluid migration and reactive mineral dissolution within the subsurface system. Fracture connectivity observed at the microscale provided additional constraints for permeability interpretation and fracture-network characterization derived from the integrated geophysical datasets. Elemental characterization was performed using energy-dispersive X-ray spectroscopy (SEM-EDS) integrated within the SEM system. Elemental mapping and spot analyses were used to identify the spatial distribution of rare earth element-bearing mineral phases including monazite, bastnäsite, xenotime, and zircon within quartz–feldspar-rich pegmatitic matrices. The SEM-EDS results also enabled identification of localized alteration zones and mineral associations relevant to dissolution behaviour and reactive surface accessibility.

X-ray Diffraction Analysis

X-ray diffraction (XRD) analysis was conducted to identify crystalline mineral phases and quantify relative mineral abundances within the pegmatitic samples. Powdered specimens were scanned over a 2θ range of 10° – 80° using a step size of 0.02° to ensure adequate mineral phase resolution and peak discrimination. Diffraction patterns revealed dominant occurrences of quartz, feldspar, muscovite, and accessory REE-bearing minerals including monazite, bastnäsite, xenotime, and zircon. Relative mineral abundances were quantified using Rietveld refinement techniques, providing mineral fraction estimates required for reactive transport simulations and dissolution kinetics modelling. The mineralogical results provided critical constraints for geochemical reaction pathways, reactive surface area estimation, and mineral dissolution behaviour within the fracture-controlled subsurface environment. Correlation between XRD-derived mineral phases, SEM-observed textures, and geophysical anomalies improved confidence in the integrated interpretation of subsurface lithological heterogeneity and mineralized zones.

BET Surface Area Analysis

Specific surface area measurements were conducted using Brunauer–Emmett–Teller (BET) adsorption analysis to quantify reactive mineral surface exposure and pore-related characteristics relevant to fluid–rock interaction processes. The measured surface area values were subsequently incorporated into permeability estimation and reactive transport simulations to constrain mineral dissolution kinetics and fluid utilization efficiency. The integrated laboratory characterization workflow provided independent validation of the interpreted geophysical structures and supplied quantitative mineralogical and petrophysical parameters required for coupled hydrogeophysical and reactive transport modelling.

Reactive Transport Modelling Framework

Reactive transport modelling was conducted to simulate fracture-controlled fluid migration, mineral dissolution behaviour, geochemical interactions, and rare earth element (REE) recovery potential within the pegmatitic subsurface system. The modelling framework integrated geophysical interpretations, laboratory-derived mineralogical parameters, petrophysical estimates, and hydrogeochemical reaction kinetics to evaluate the spatial and temporal evolution of fluid–rock interaction processes within structurally heterogeneous pegmatitic formations. The coupled hydrogeophysical modelling workflow incorporated fracture-network characterization, permeability estimation, porosity distribution, reactive surface area determination, and mineralogical phase quantification derived from integrated ERT, seismic, SEM, XRD, and BET analyses. The resulting parameter distributions were subsequently incorporated into the reactive transport simulations to constrain subsurface flow behaviour and mineral dissolution dynamics within fracture-controlled pathways. Fracture-controlled fluid transport within the subsurface environment was simulated using coupled advection–dispersion–reaction relationships governing reactive solute migration through porous and fractured media. Preferential flow pathways interpreted from integrated geophysical datasets were represented as hydraulically conductive fracture zones characterized by enhanced permeability and interconnected pore structures.

Governing Equations and Dissolution Kinetics

Mineral dissolution kinetics within the pegmatitic system were simulated using a geochemically controlled rate expression relating reactive surface area, equilibrium concentration, and mineral reaction kinetics:

$$R = kA(C_{eq} - C) \quad (iv)$$

where R represents the mineral dissolution rate, k is the reaction rate constant, A is the reactive mineral surface area derived from BET and SEM analyses, C_{eq} is the equilibrium concentration of dissolved mineral species, and C is the instantaneous aqueous concentration within the reacting fluid system. The dissolution model accounted for mineral heterogeneity, fracture-enhanced fluid accessibility, reactive surface exposure, and geochemically controlled equilibrium constraints. Reactive surface area values were constrained using laboratory-derived BET adsorption measurements and SEM-observed fracture textures to improve simulation realism and dissolution-rate prediction. Fluid transport within the fracture-controlled subsurface environment was further represented using the advection–dispersion transport equation

$$\frac{\partial C}{\partial t} + \nabla \cdot (vC - D\nabla C) = R \quad (V)$$

where C represents dissolved species concentration, t denotes time, v is fluid velocity, D is the hydrodynamic dispersion coefficient, and R represents the reactive source or sink term associated with mineral dissolution and precipitation processes. The transport model incorporated fracture-enhanced permeability distributions, diffusion-controlled solute exchange, and localized dissolution fronts associated with structurally connected pegmatitic zones. Simulated dissolution behaviour was strongly influenced by fracture connectivity, fluid residence time, mineral abundance, and reactive surface exposure.

Fracture-Controlled Flow Representation

Fracture systems interpreted from integrated geophysical and structural datasets were represented within the modelling framework as preferential fluid migration pathways characterized by elevated permeability and interconnected porosity. Fracture connectivity was constrained using resistivity anomalies, seismic velocity reductions, mapped structural lineaments, and borehole observations. Hydraulic conductivity distributions derived from petrophysical transforms were assigned to individual model domains to represent spatial heterogeneity within the pegmatitic formations. High-permeability fracture corridors were associated with low-resistivity and low-seismic-velocity anomalies interpreted from the integrated geophysical models. Fluid migration simulations demonstrated preferential propagation of reactive fluids through interconnected fracture systems, resulting in localized enhancement of mineral dissolution and REE mobilization within structurally altered pegmatitic zones.

Boundary and Initial Conditions

The reactive transport simulations were initialized using lithological, petrophysical, and hydrogeochemical parameters derived from integrated geophysical interpretation and laboratory characterization. Initial porosity, permeability, mineral abundance, and fluid saturation conditions were assigned based on borehole observations, SEM analyses, XRD-derived mineral fractions, and petrophysical parameter estimation. Boundary conditions incorporated controlled fluid injection along fracture-dominated zones identified from the integrated geophysical datasets. Constant-pressure inflow boundaries were assigned along hydraulically conductive fracture corridors, while no-flow boundary conditions were imposed along relatively competent low-permeability basement domains. Initial aqueous geochemical conditions were constrained using equilibrium concentrations associated with dominant pegmatitic mineral phases. Transport simulations further incorporated temperature-dependent reaction kinetics, hydrodynamic dispersion effects, and diffusion-controlled mass transfer processes within the fractured porous medium.

Model Integration and Calibration

Integrated geophysical outputs constrained fracture connectivity, porosity distribution, hydraulic conductivity, and permeability variability within the subsurface environment, while laboratory-derived mineralogical analyses quantified reactive mineral abundance, surface area, and dissolution susceptibility. The combined workflow enabled realistic simulation of fracture-controlled fluid transport and mineral dissolution processes within the pegmatitic system. Calibration of the modelling framework was achieved through comparison between simulated dissolution behaviour, laboratory-derived mineralogical observations, and geophysical interpretations of fracture-controlled flow pathways. Sensitivity analyses were additionally conducted to evaluate the influence of permeability variability, reactive surface area, and fracture connectivity on predicted mineral recovery behaviour. Optimal mineral recovery zones were identified through spatial correlation of high-permeability fracture systems, elevated reactive surface area, and enhanced dissolution potential within the integrated subsurface models.

Evaluation Metrics

Reactive transport performance and mineral recovery behaviour were evaluated using multiple quantitative indicators describing extraction efficiency, fluid utilization, and environmental response within the fracture-controlled subsurface system. Recovery efficiency was evaluated as the fraction of dissolved and recoverable REE-bearing mineral phases relative to the estimated total mineral abundance within the modeled domain. Fluid utilization efficiency was quantified as the ratio between effective reactive fluid volume participating in mineral dissolution and the total injected fluid volume. Additional environmental performance indicators included assessment of potential contaminant mobilization, dissolved species migration, and geochemical alteration associated with fluid–rock interaction processes within the fractured pegmatitic formations. The integrated hydrogeophysical and reactive transport modelling workflow provided improved constraints on fracture-controlled mineral recovery behaviour, reactive fluid migration pathways, and dissolution kinetics within REE-bearing pegmatitic subsurface systems.

3. Results and Discussion

Geophysical Interpretation Results

Integrated electrical resistivity tomography and seismic refraction analyses revealed pronounced subsurface heterogeneity associated with fracture-controlled pegmatitic mineralization within the study area. The combined geophysical datasets enabled delineation of structurally altered zones, weathered basement interfaces, fluid migration pathways, and lithological variability relevant to rare earth element (REE) mobilization and recovery. The resistivity inversion sections revealed subsurface resistivity variations ranging approximately from low-conductivity fractured zones to highly resistive competent pegmatitic basement units. Low-resistivity anomalies were predominantly associated with structurally altered regions characterized by enhanced fracture density, fluid saturation, and increased porosity. These conductive zones were interpreted as preferential pathways for reactive fluid migration during simulated mineral recovery processes. High-resistivity regions corresponded to relatively competent crystalline basement rocks dominated by quartz–feldspar-rich pegmatitic units exhibiting reduced fracture connectivity and lower fluid transmissivity. Intermediate resistivity zones likely represented partially weathered pegmatitic domains characterized by moderate fracture development and localized mineral alteration. The seismic velocity tomography sections revealed compressional wave velocities ranging approximately from 3.0 km/s within fractured and weathered regions to over 6.0 km/s within relatively competent basement units. Reduced seismic velocities were spatially correlated with low-resistivity anomalies, confirming the occurrence of structurally weakened and fluid-accessible zones within the subsurface environment. Integrated interpretation of the geophysical datasets identified interconnected fracture corridors extending through the pegmatitic formations. These fracture-controlled pathways are considered critical for reactive fluid transport, dissolution-front propagation, and enhanced REE mobilization within the modeled subsurface system. Correlation between geophysical anomalies, borehole observations, and mapped structural lineaments improved confidence in the interpretation of fracture-controlled mineralized zones. The integrated geophysical workflow therefore provided important constraints for permeability estimation, reactive transport simulations, and identification of preferential mineral recovery targets within the pegmatitic subsurface environment.

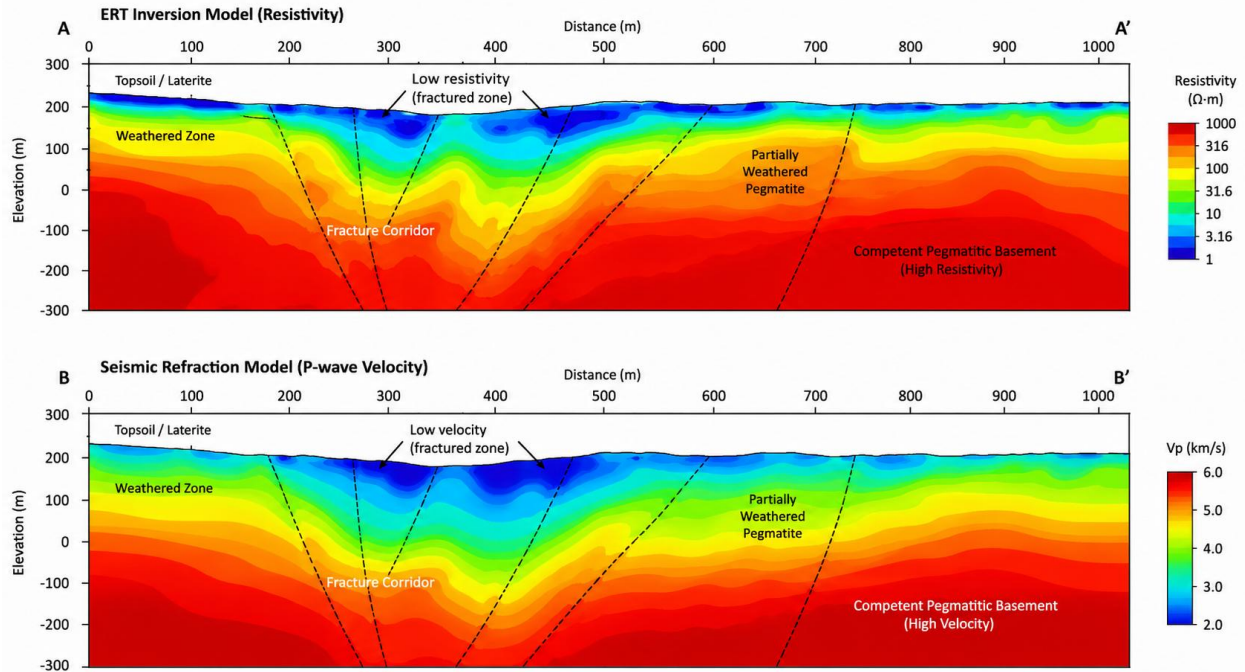


Figure 5: Integrated electrical resistivity tomography (ERT) inversion and seismic refraction tomography sections showing subsurface lithological variability, fracture-controlled structural zones, fluid migration pathways, and interpreted pegmatitic mineralization within the study area.

The integrated interpretation of electrical resistivity tomography and seismic refraction datasets presented in Figure 5 is consistent with previous hydrogeophysical investigations that demonstrated the importance of coupled geophysical methods for subsurface structural characterization and fluid-flow evaluation within heterogeneous geological environments. Revil [20] established that electrical conductivity variations within geological formations are strongly controlled by pore-fluid distribution, fracture connectivity, and lithological heterogeneity, thereby supporting the interpretation of conductive fracture-controlled pathways identified in the present study. Similarly, Dvorkin et al. [19] demonstrated that seismic velocity variations provide important constraints on rock properties, porosity distribution, and structural competency within fractured subsurface systems, which agrees with the seismic interpretation framework adopted in this investigation.

Petrophysical Parameter Results

Petrophysical parameter estimation revealed substantial spatial variability in porosity, permeability, hydraulic conductivity, and fracture connectivity across the investigated pegmatitic subsurface system. These variations strongly influenced fluid migration behaviour and dissolution efficiency within the reactive transport simulations. Porosity estimates derived from Archie's Law and seismic velocity transforms indicated elevated porosity values within low-resistivity and low-seismic-velocity regions interpreted as fractured and structurally altered zones. These regions exhibited enhanced pore connectivity and increased fluid accessibility relative to the surrounding competent basement domains. Permeability distributions estimated

using the modified Kozeny–Carman relationship demonstrated strong spatial correlation with mapped fracture density and geophysically interpreted structural corridors. High-permeability zones were concentrated within interconnected fracture systems characterized by reduced resistivity and lower seismic velocities. Hydraulic conductivity distributions further confirmed the dominant role of structural heterogeneity in controlling subsurface fluid migration pathways. Enhanced hydraulic conductivity within fracture-dominated domains promoted increased reactive fluid penetration and localized mineral dissolution within the pegmatitic formations. The integrated petrophysical workflow demonstrated strong coupling between geophysical anomalies, fracture-network development, and hydraulic transport behaviour. These derived hydraulic parameters subsequently provided essential constraints for reactive transport modelling and recovery prediction within the fracture-controlled REE-bearing subsurface system.

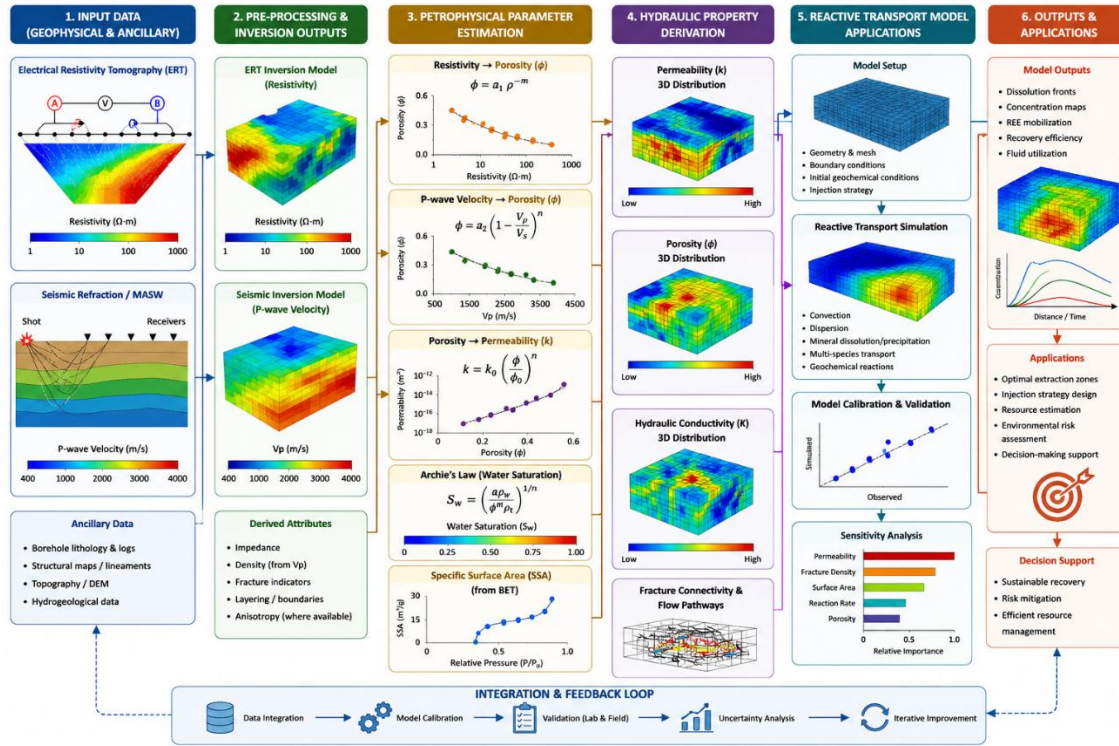


Figure 6: Integrated petrophysical parameter estimation workflow illustrating the transformation of geophysical datasets into hydraulic and fracture-related parameters for coupled reactive transport simulation and fracture-controlled rare earth element recovery within pegmatitic subsurface systems.

The petrophysical parameter estimation workflow illustrated in Figure 6 aligns with established approaches linking geophysical datasets with hydraulic and transport-related properties in fractured geological systems. Berkowitz [21] emphasized that fracture connectivity and hydraulic heterogeneity exert dominant controls on subsurface flow and transport processes, supporting the integration of permeability and fracture-network characterization employed in the present study. Similarly, Lichtner [22] demonstrated that reactive transport behaviour within geological media is highly dependent on coupled hydraulic and geochemical parameterization,

thereby validating the transformation of geophysical observations into reactive transport model inputs within the developed workflow.

Mineralogical Characterization Results

SEM imaging and XRD analyses confirmed the occurrence of REE-bearing mineral phases within the pegmatitic formations and revealed significant microstructural heterogeneity associated with fracture-controlled alteration processes. SEM observations revealed interconnected micro-fractures, dissolution textures, grain-boundary alteration features, and pore-scale structural discontinuities within the pegmatitic samples. These fracture systems are interpreted to enhance reactive fluid accessibility and promote localized mineral dissolution during simulated recovery processes. SEM-EDS elemental mapping identified the occurrence of REE-bearing minerals including monazite, bastnäsite, xenotime, and zircon within quartz–feldspar-rich pegmatitic matrices. The observed mineral associations indicate structurally controlled mineral distribution and localized enrichment within fracture-influenced zones. XRD analyses confirmed dominant occurrences of quartz, feldspar, muscovite, and accessory REE-bearing mineral phases. Rietveld refinement provided quantitative mineral fraction estimates subsequently incorporated into the reactive transport simulations to constrain mineral abundance and dissolution kinetics. Correlation between SEM-observed fracture textures, XRD-derived mineral phases, and geophysical anomalies improved confidence in the integrated interpretation of fracture-controlled mineralization within the pegmatitic system. The laboratory characterization results therefore provided important validation for the coupled hydrogeophysical modelling framework.

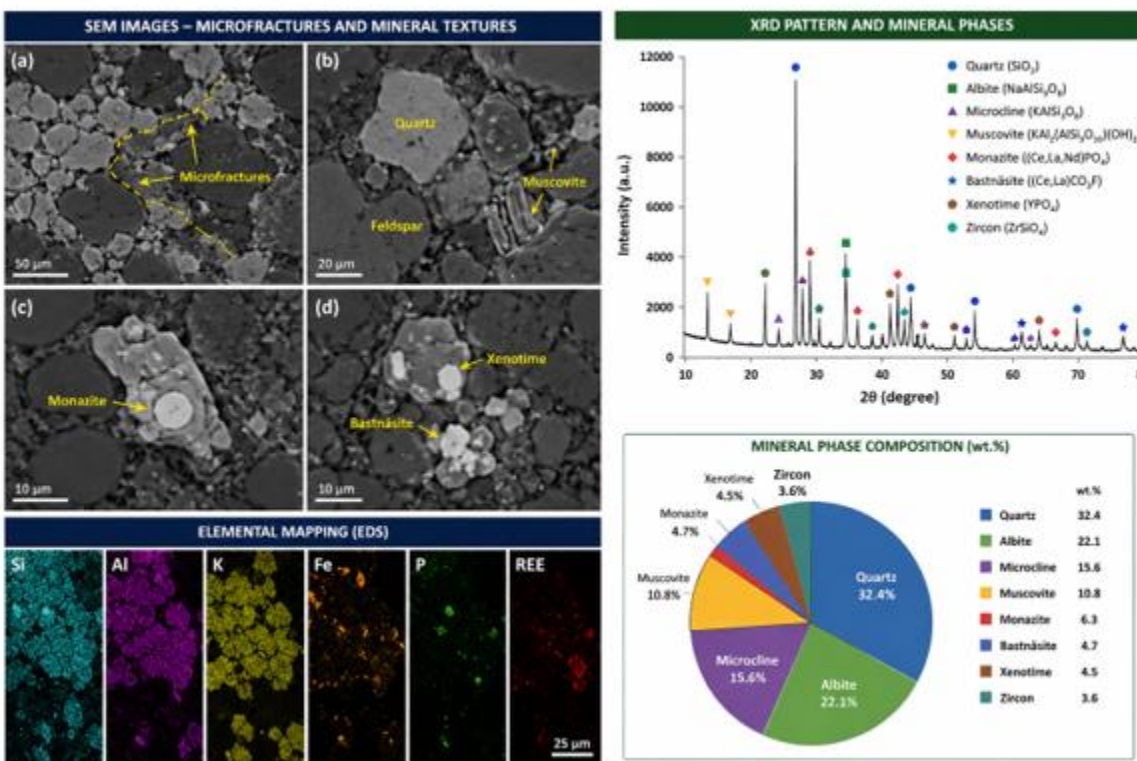
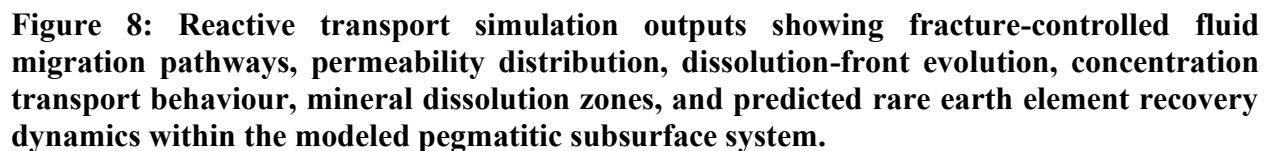
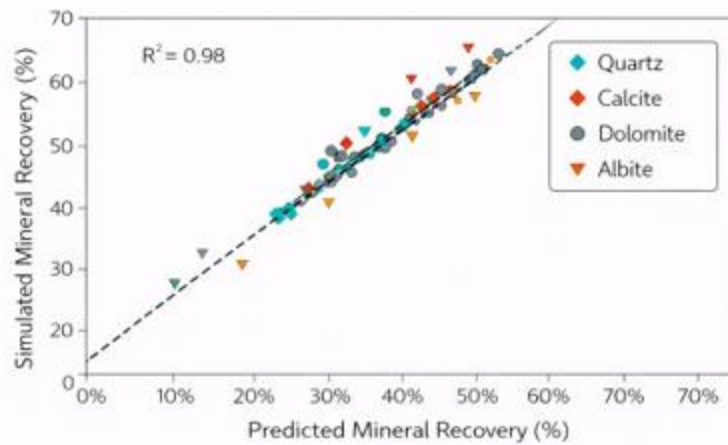


Figure 7: SEM micrographs, SEM-EDS elemental distribution maps, and XRD mineral phase characterization of REE-bearing pegmatitic samples showing microfracture development, mineral textures, elemental associations, and crystalline phase composition relevant to fracture-controlled reactive transport and rare earth element recovery.

The mineralogical and microstructural characterization results presented in Figure 7 are consistent with previous investigations highlighting the importance of pore-scale heterogeneity and mineral-surface interactions in governing reactive transport processes within fractured geological environments. Molins et al. [24] demonstrated that pore-scale flow dynamics and mineral surface accessibility strongly influence dissolution-front evolution and reactive transport behaviour, supporting the observed microfracture-controlled dissolution features identified in the SEM analyses. In addition, Nassar et al. [18] emphasized the growing technological importance and supply challenges associated with critical and rare earth element-bearing mineral systems, thereby reinforcing the significance of detailed mineralogical characterization for sustainable subsurface REE resource evaluation.

Reactive Transport Simulation Results

Reactive transport simulations demonstrated strong dependence of mineral dissolution behaviour and REE mobilization on fracture connectivity, permeability variability, reactive surface area distribution, and fluid migration pathways within the pegmatitic subsurface system. Simulated fluid migration preferentially propagated through interconnected fracture corridors characterized by elevated permeability and enhanced hydraulic conductivity. These structurally controlled pathways promoted localized dissolution-front development and increased reactive fluid accessibility to REE-bearing mineral phases. The simulations revealed progressive dissolution of fracture-accessible mineral surfaces with increasing fluid residence time and fracture connectivity. Zones characterized by high reactive surface area and elevated fracture density exhibited enhanced dissolution efficiency relative to structurally competent low-permeability regions. Temporal concentration evolution within the modeled domain indicated progressive mobilization of dissolved REE species along preferential fracture-controlled flow pathways. The transport behaviour was strongly influenced by porosity distribution, diffusion-controlled mass transfer, and localized mineral abundance. Sensitivity analysis demonstrated that permeability variability, fracture connectivity, reactive surface area, and dissolution-rate constants exerted the strongest influence on predicted recovery behaviour. Increased fracture connectivity generally promoted enhanced mineral dissolution and improved fluid utilization efficiency within the modeled system. The coupled hydrogeophysical and reactive transport modelling framework therefore demonstrated the critical role of fracture-controlled fluid migration in governing REE mobilization and mineral recovery behaviour within pegmatitic subsurface systems.



The reactive transport simulation outputs shown in Figure 8 are in agreement with previous studies demonstrating the importance of coupled hydrogeochemical modelling for predicting fluid migration and mineral reaction behaviour within fractured subsurface systems. Steefel et al. [23] described reactive transport modelling as an essential tool for understanding coupled fluid–rock interaction processes and geochemical evolution within complex geological environments, which directly supports the modelling framework developed in this study. Similarly, Matter and Kelemen [25] demonstrated that fracture-controlled fluid transport and mineral reaction kinetics strongly influence subsurface geochemical processes and long-term mineral transformation within geological formations, consistent with the fracture-enhanced dissolution and transport behaviour predicted in the present simulations.

Integrated Interpretation and Model Validation

Integrated interpretation of the geophysical, petrophysical, mineralogical, and reactive transport datasets demonstrated strong coupling between fracture-network development, hydraulic transport behaviour, and mineral dissolution efficiency within the pegmatitic subsurface system. Spatial correlation between low-resistivity anomalies, reduced seismic velocities, elevated permeability, and enhanced fracture density confirmed the dominant influence of structurally controlled pathways on fluid migration and reactive transport processes. Laboratory characterization further validated the occurrence of fracture-enhanced reactive surface exposure and REE-bearing mineral phases within the interpreted mineralized zones. The consistency between geophysical interpretations, mineralogical observations, and reactive transport predictions improved confidence in the predictive capability of the integrated modelling workflow. The combined methodology therefore provides a reproducible framework for evaluating fracture-controlled mineral recovery behaviour within structurally heterogeneous pegmatitic environments. Sensitivity analysis indicated that permeability distributions, fracture connectivity, reactive surface area, and dissolution-rate parameters represent the dominant sources of uncertainty within the coupled simulations. Despite these uncertainties, the integrated workflow successfully constrained fluid migration behaviour and mineral dissolution dynamics through incorporation of laboratory-derived mineralogical and petrophysical parameters. The integrated hydrogeophysical framework therefore demonstrates significant potential for improving subsurface characterization, reactive transport prediction, and resource evaluation within REE-bearing pegmatitic systems.

Limitations and Uncertainty Analysis

Despite the improved integration of geophysical interpretation, mineralogical characterization, and reactive transport modelling, uncertainties remain associated with fracture-network representation, hydraulic parameter estimation, and geochemical reaction kinetics within the subsurface environment. Permeability estimation from geophysical datasets is inherently influenced by assumptions relating resistivity and seismic velocity to porosity and hydraulic conductivity. Similarly, fracture connectivity within the modeled domain may vary spatially beyond the resolution limits of the integrated geophysical datasets. Reactive transport simulations are additionally sensitive to uncertainties in dissolution-rate constants, reactive surface area estimates, diffusion coefficients, and equilibrium reaction parameters. Although laboratory-derived BET, SEM, and XRD analyses provided important constraints, natural

subsurface heterogeneity may introduce localized variability not fully captured within the simulations. Future investigations should incorporate direct hydrogeological testing, tracer experiments, high-resolution fracture mapping, and field-scale reactive transport validation to further constrain hydraulic behaviour and improve predictive reliability within fracture-controlled REE-bearing pegmatitic systems.

Conclusion

This study developed an integrated hydrogeophysical and reactive transport modelling framework for evaluating fracture-controlled rare earth element recovery within pegmatitic subsurface systems. The combined workflow incorporated electrical resistivity tomography, seismic refraction analysis, petrophysical parameter estimation, mineralogical characterization, and coupled reactive transport simulations to investigate the influence of structural heterogeneity on fluid migration and mineral dissolution behaviour. Integrated geophysical interpretation successfully delineated fracture-controlled pathways characterized by low resistivity, reduced seismic velocity, elevated porosity, and enhanced permeability. Laboratory characterization through SEM, SEM-EDS, XRD, and BET analyses further confirmed the occurrence of REE-bearing mineral phases and provided quantitative constraints for reactive transport simulations. Reactive transport modelling demonstrated that fracture connectivity, reactive surface area, permeability variability, and hydraulic conductivity exert strong controls on dissolution-front propagation and REE mobilization within pegmatitic formations. Sensitivity analysis further identified permeability and fracture-network connectivity as dominant parameters influencing predicted recovery behaviour. The integrated workflow provides a reproducible and geologically constrained framework for evaluating fracture-controlled mineral recovery processes within structurally heterogeneous subsurface environments. The methodology additionally demonstrates the importance of coupling geophysical characterization with laboratory-derived mineralogical validation and reactive transport simulations for improved prediction of fluid–rock interaction processes within REE-bearing pegmatitic systems. Future studies should incorporate field-scale hydrogeological testing, tracer experiments, and long-term monitoring to further validate reactive transport behaviour and improve predictive reliability for sustainable subsurface rare earth mineral recovery applications.

Data Availability

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

All authors contributed equally to the conception, design, analysis, and writing of the manuscript.

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Competing Interests

The authors declare no competing interests.

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