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Rare Earth Elements (REEs) Potential in Active Geothermal Systems: A Global Review and Regional Study at Mount Slamet, Indonesia

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ABSTRACT

As global demand for REEs continues to rise due to their strategic role in clean energy technologies, geothermal systems offer an emerging unconventional source. Although data on Indonesian geothermal REEs remain limited, geochemical signals from Mount Slamet provide valuable insights when interpreted alongside global analogs. This study investigates the occurrence, mobility, and potential of rare earth elements (REEs) in the active geothermal system of Mount Slamet, Central Java, Indonesia, with a focus on the hot spring manifestations in Baturraden and Guci using a systematic literature review method based on published research. Baturraden exhibits neutral fluids (pH 6–7) with elevated chloride levels, suggesting enhanced REEs mobilization and strong positive europium (Eu) anomalies under deeper reducing conditions. In contrast, Guci displays more alkaline fluids (pH ~8) with lower chloride content, indicating possible meteoric water dilution and lower REEs transport efficiency. These contrasting hydrochemical profiles highlight diverse water-rock interaction mechanisms and fluid pathways. The findings highlight Mount Slamet as a promising candidate for REEs exploration in a volcanic-related geothermal system. This study underscores the urgent need for systematic research on REEs geochemistry in Indonesian geothermal fields to support mineral diversification and sustainable energy transitions.

Keywords: Mount Slamet, REEs, geothermal, critical minerals, hydrogeochemistry

INTRODUCTION

Rare Earth Elements (REEs) have emerged as a strategically critical element group irreplaceable in the modern global technology and energy landscape. Their increasing demand, which is primarily driven by the transition toward clean and sustainable energy, has intensified global efforts to explore unconventional sources of mineral resources. Among these, geothermal systems, particularly those associated with volcanic activity, are increasingly recognized as potential hosts for REEs mobilization and accumulation [1].

The extraction of critical minerals from geothermal fluids has thus attracted considerable international attention, offering a promising pathway for diversifying mineral supply chains. An increasing number of case studies from various geothermal systems worldwide have confirmed the presence of REEs and other critical minerals in hydrothermal environments (Table 1), highlighting their potential as an alternative resource base [2].

In this context, Mount Slamet, a Quaternary basaltic stratovolcano located in Central Java, Indonesia, represents a valuable case study. As part of the extensive Sunda volcanic arc [3], Mount Slamet hosts a geothermal system characterized by three main surface manifestations: Baturraden (southern slope), Guci (northern slope), and Paguyangan (western slope) [2]. These sites exhibit surface hot spring temperatures ranging from 42°C to 72°C, providing a natural laboratory to assess hydrothermal processes and the potential for REEs mobilization within a volcanic-related geothermal setting [2].

Table 1. Global Examples of REEs/Critical Mineral Occurrence in Geothermal Systems [1], [4]–[6]

Geothermal System Location	Identified REEs/ Critical Minerals	Enrichment Characteristics	Main Source/Mechanism of Enrichment
Tibetan Plateau, China [1]	Lithium (Li), Rubidium (Rb), Cesium (Cs), Boron (B)	Significant enrichment in hot springs and sediments, substantial flux of resources	Magmatic-hydrothermal fluids from partial melting of subducted plates
Salton Sea, California, USA [4]	Lithium (Li)	High extraction potential (>24,000 metric tons/year); DLE technology (adsorption, ion exchange) under testing	Geothermal brine, more economical and environmentally friendly than traditional mining
Oregon, Nevada, California, USA [5]	REEs (generally LREE-enriched)	Low to moderate concentrations in thermal water; positive Eu anomaly at Heber	Leaching of host rocks or reducing conditions (Eu anomaly)
Tuzla, Turkey [6]	Lithium (Li)	Relatively high Li concentration (~25 mg/L) in brine; sorption method for recovery	Geothermal brine

The diversity of geothermal surface manifestations surrounding Mount Slamet, which is driven by volcanic activity and interactions with varying lithologies, including marine sedimentary rocks, reflects the inherent complexity of its hydrothermal system. Variations in surface geochemistry, such as the nature of travertine deposits and wall rock composition (volcanic versus sedimentary), point to different water-rock interaction regimes operating beneath the volcano. These contrasting geochemical and lithological conditions are likely to result in spatially heterogeneous REEs enrichment and distribution patterns. Consequently, each geothermal site around Mount Slamet must be evaluated independently to determine its REEs potential, reinforcing its relevance as a key target for detailed geochemical investigations of critical minerals.

On a broader scale, Indonesia possesses vast geothermal energy potential, estimated at 23.5 GW. However, only 2.6 GW has been harnessed to date, with a national target of 10.5 GW by 2035. As the world's second-largest country in terms of installed geothermal power capacity, Indonesia is well-positioned to leverage geothermal energy as a backbone of its clean energy transition, aligned with its 2060 net-zero emission commitment [7].

Despite this progress, scientific understanding of REEs behavior within Indonesia's geothermal systems remains severely limited. Existing studies on lithium, which is often associated with REEs, have been limited to a few geothermal sites worldwide. Notable examples include the Tibetan Plateau, China; the Salton Sea, California; and Tuzla, Turkey. Furthermore, although REEs enrichment has been reported in Wayang Windu in West Java, with

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concentrations ranging from 1 to 500 ppm [8], such data remain fragmentary and lack comprehensive coverage across other active geothermal systems, including Mount Slamet.

The lack of comprehensive and publicly accessible data on REEs geochemistry in Indonesian geothermal systems hinders proper resource assessment and the development of targeted extraction strategies. This issue is further compounded by the limited number of scientific publications and the confidentiality surrounding exploration data, which restricts broader understanding of the critical mineral potential in these systems. Mount Slamet, with its diverse geothermal manifestations, represents a promising but underexplored target for such studies.

To address this gap, this article reviews reputable international literature on REEs in active geothermal systems to build a conceptual framework applicable to Mount Slamet. The review includes peer-reviewed articles and conference proceedings from the last 20–25 years, sourced from Scopus, Web of Science, and SINTA databases, using keywords such as "rare earth elements", "geothermal fluids", and "critical minerals". Emphasis is placed on case studies from volcanic geothermal settings with geological similarities to Indonesia.

The review focuses on geochemical mechanisms controlling REEs mobilization, transport, and deposition, including pH, temperature, redox conditions, and ligand availability. These insights are then applied to the geothermal context of Mount Slamet, particularly Baturraden, Guci, and Paguyangan, to evaluate the potential of local REEs and identify key research gaps for future exploration.

MAIN SUBJECTS

This review-based scientific paper explores the geochemical behavior, occurrence, and exploration potential of REEs within active geothermal systems, focusing on the volcanic-related geothermal setting of Mount Slamet in Central Java, Indonesia. It synthesizes global findings from peer-reviewed literature spanning the last two decades, covering REEs solubility, transport mechanisms, chemical speciation, and the influence of physicochemical factors such as pH, redox conditions, temperature, and ligand availability (e.g., carbonate, sulfate, and chloride complexes).

The main subject of this review includes: (1) Assessment of international case studies from major geothermal sites such as Tibetan Plateau (China), Salton Sea (US), Oregon-Nevada (US), and Tuzla (Turkey), where REEs presence in geothermal fluids has been documented. (2) A conceptual analysis of REEs mobility and partitioning in fluid-rock interaction environments. (3) A critical comparison between global systems and the dual geothermal manifestations of Mount Slamet (Baturraden and Guci), highlighting contrasts in pH, fluid pathways, chloride/boron ratios, and carbonate precipitation.

This work positions the Mount Slamet geothermal area as a relevant analog for studying REEs in underexplored volcano-related geothermal systems. It also identifies key knowledge gaps, particularly the absence of REEs concentration data from Indonesian geothermal fluids, and proposes future research directions involving fluid sampling, REEs quantification, and isotopic analyses. The paper contributes to developing a geochemically informed framework for REEs co-prospecting in geothermal reservoirs across the Indonesian magmatic arc.

CONCEPTUAL FRAMEWORK: REEs IN GEOTHERMAL SYSTEMS

REEs occur in geological fluids, with concentrations in geothermal fluids typically ranging from sub-ppb to low ppm levels [9]. pH was identified as the main controlling factor influencing the absolute concentrations and normalized REEs patterns of chondrites in hydrothermal fluids [10]. Acidic sulfate waters with low pH are consistently associated with the highest REEs concentrations, where most REEs are in proper solution [11]. Studies show that REEs concentrations in geothermal fluids are inversely proportional to pH rather than directly to rock type or temperature [9].

REEs form their strongest complexes with various ligands, including hydroxides, fluorides, carbonates, sulfates, and phosphates [12] (see Table 2). In acidic to neutral hydrothermal systems, REEs transport is mainly governed by sulfate (SO_4^{2-}) and chloride (Cl^-) ions. Although chloride complexes are weak at ambient temperatures, their stability increases significantly with increasing temperature [13]. In neutral to alkaline hydrothermal systems, REEs are mainly present in fluids as hydroxyl complexes or other ligand-bearing hydroxyl complexes. Carbonate and bicarbonate ions are also capable of forming complexes with REE [13]. Fluoride (F^-) is often associated with REEs deposits. It may influence REEs transport, although its exact role (direct transport agent vs. crystallization/enrichment influence) is still debatable [13].

Although pH has significant control, the effects of temperature and salinity on the overall REEs abundance in hydrothermal fluids are relatively small. However, high temperatures can promote the release of more soluble Medium REEs (MREEs) from the source rock [11]. Several studies have also shown increased adsorption of REEs on organic surfaces at temperatures up to around 70°C [9]. High-temperature solutions (over 230°C) originating from different rock types can sometimes show similar REEs distribution patterns [10]. Filtered geothermal fluid aliquots often show much lower REEs concentrations than unfiltered samples, indicating a substantial contribution of REEs associated with suspended particulate matter [12].

Table 2. Key ligands and their role in REEs complexation and mobility in hydrothermal fluids [9]–[13]

Ligand	Chemical Formula	Dominant pH Range for Complexation	Effect on REEs Mobility
Hydroxide	OH^-	Neutral to Alkaline	Forms hydroxyl complexes; dominant in neutral-alkaline fluids.
Fluoride	F^-	Acidic to Neutral	Forms stable complexes; role in REEs transport vs. deposition remains debated.
Carbonate	CO_3^{2-}	Neutral to Alkaline	Forms complexes; REEs precipitation may occur when CO_2 levels decrease.
Sulfate	SO_4^{2-}	Acidic to Neutral	Major ligand for REEs transport in acidic to near-neutral systems.
Chloride	Cl^-	Acidic to Neutral	Forms weak complexes at 25°C; stability increases significantly at higher temperatures.
Phosphate	PO_4^{3-}	Not Specific	Forms strong complexes.

RESULTS AND DISCUSSION

Global Case Study on the Occurrence of REEs in Volcano-Related Geothermal Systems

The potential for extracting critical minerals from geothermal fluids has attracted global attention as a promising unconventional resource. Case studies worldwide have identified and confirmed the presence of REEs and other critical minerals in active geothermal systems (see Table 1).

On the Tibetan Plateau, geothermal systems show significant enrichment in lithium (Li), rubidium (Rb), cesium (Cs), and boron (B) in hot springs and sediments, with substantial resource flux estimates. Magmatic-hydrothermal fluids from the partial melting of the subducted Indian plate are believed to be the primary source of material and heat [1], [14].

The Salton Sea region of California, USA, is a leading example of great potential for lithium extraction from geothermal fluids, with an estimated annual yield of over 24,000 metric tons of lithium. Various direct extraction (DLE) technologies, such as adsorption and ion exchange, are being developed and pilot-scaled, offering the potential for a safe and sustainable domestic supply of lithium. Direct extraction methods from geothermal fluids are more sustainable and potentially economical than traditional mining [4].

Studies of thermal waters from hot springs in the Oregon Cascades and Nevada (Beowawe, Dixie Valley) and California (Heber), USA, show variable, generally low ($<10^{-6}$ to about 10^{-3} times chondrite) REEs concentrations. Most show LREE-enriched REEs patterns. The positive Europium anomaly at Heber is attributed to source rock dissolution or reducing conditions [5]. In Tuzla, Türkiye, geothermal fields show relatively high lithium concentrations (about 25 mg/L), and sorption methods are being tested for their recovery [6].

The success and ongoing research at various global sites show that REEs extraction from geothermal is no longer a theoretical concept but a viable pathway to diversify critical mineral supplies. This suggests that geothermal energy can be a "dual" resource, not only for renewable energy but also for critical minerals essential to the energy transition.

Magma Characteristic and Evolution of Mount Slamet to The Occurrence of REEs in Volcanic-Related Geothermal Systems

The magmatism of Mount Slamet is characterized by a compositional range from basaltic to andesitic, indicating a calc-alkaline affinity. This geochemical feature is characteristic of magmatism associated with subduction zones [3]. Volcanic rocks from the Mount Slamet area (especially Guci and Baturraden) show a calc-alkaline character with low to moderate potassium content, typical of Central Java. Compared to nearby volcanoes such as Sundoro and Ciremai, Slamet shows a higher K_2O content, indicating crustal contamination during the ascent and evolution of the magma [15].

Compared to other volcanoes in Central Java, the high K_2O content in the volcanic rocks of Mount Slamet strongly indicates crustal contamination [15]. Crustal contamination can significantly change the REEs characteristics of magma [15]. The interaction between magma and various rock types (both volcanic and sedimentary) directly alters the fluid chemistry in geothermal manifestations, which in turn governs the efficiency of rare earth element (REEs) mobilization. This mobilization typically occurs during water–rock interaction processes [15]. Assimilated crustal materials, such as sedimentary rocks, often exhibit distinctive REEs signatures or contain specific REEs-bearing minerals, and their incorporation during magmatic processes can modify the overall REEs composition and distribution. This highlights the complex interplay between deep magmatic processes and shallow crustal interactions in determining the overall REEs potential of a volcanic system and volcanic-related geothermal systems [3].

Differentiation of Old Slamet and Young Slamet Magma Series

Slamet volcanism is divided into two main stages: the Old Slamet and Young Slamet sequences (Figure 1). The **Old Slamet** stage is characterized by basaltic to andesitic compositions (SiO_2 ranging from 49-59%) and is associated with a coarse morphology on the volcano's western flank. Geochemical evidence suggests that Old Slamet produces predominantly andesitic rocks. Its magmatic evolution is more intensive, resulting in a broader silica content spectrum and may correlate with past explosive eruptive events [3]. The **Young Slamet** stage is defined by a more mafic composition, ranging from basaltic to basaltic andesite (SiO_2 48-52%), and is associated with a finer morphology on the eastern flank. The Young Slamet sequence, particularly represented by the Guci and Baturraden unit, is dominated by mafic magmas. Geochemically, Young Slamet produces mainly basaltic rocks [3].

Both Old Slamet and Young Slamet magmas are consistently classified as calc-alkaline. The compositional and morphological differences between Old Slamet and Young Slamet suggest that they originate from different magma chambers. Magma differentiation processes, especially fractional crystallization and magma mixing, are the main mechanisms driving the evolution of Slamet magmas. Old Slamet magmas generally show lower total REEs contents with slight negative Europium (Eu) anomalies. In contrast, Young Slamet magmas show similar Light REEs (LREEs) patterns but with higher concentrations of Medium REEs (MREEs) and Heavy REEs (HREEs) [3]. Although this study does not directly report chondrite-normalized REEs concentrations from geothermal fluids, valuable comparative data are available from the rock geochemistry of Slamet Volcano. Previous study from Vukadinovic and Sutawidjaja (1995) presented chondrite-normalized REEs patterns for various lava sequences, showing that HAM (high-abundance magma) lavas display flat HREE profiles with stronger Eu anomalies (Eu/Eu* ~0.82–0.88), while LAM (low-abundance magma) lavas show concave-upward HREE trends with weaker Eu anomalies (Eu/Eu* ~0.94). These patterns provide a geochemical baseline that can guide future interpretation of REEs behavior in associated hydrothermal fluids, especially when evaluating potential enrichment or fractionation in the Mount Slamet geothermal system [16].

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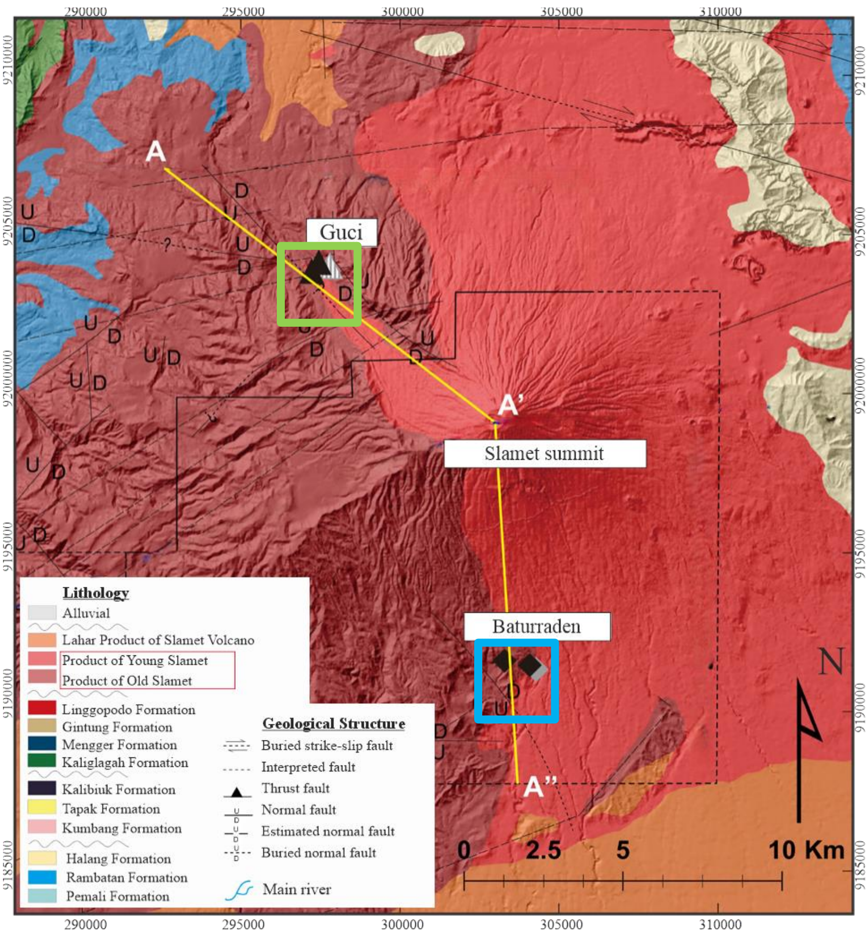

Figure 1. Modification of the Regional Geological Map of Purwokerto-Tegal Sheet [17], [18], showing the location of the Baturraden (blue square) and Guci (green square) geothermal manifestation areas [19]

Does Slamet Fluid Have Suitable Conditions to Carry REEs?

Mount Slamet hosts two principal geothermal complexes, Baturraden to the south and Guci to the north, both of which exhibit potential for rare earth element (REE) transport. The hydrogeological cross-section along the Guci–Slamet Summit–Baturraden transect (Figure 2) indicates contrasting subsurface fluid chemistries that influence REE mobility.

Surface temperatures range from 42–72°C [2], below the >250°C threshold typically associated with strong positive Eu anomalies; however, reservoir temperatures at depth are likely higher, enhancing REE solubility. Fluid acidity differs between the sites, with Baturraden waters (pH 6–7) being slightly more acidic than the alkaline fluids at Guci (pH ≈ 8) [2]. This acidity, coupled with literature evidence linking low pH to elevated REE concentrations [9], [20], suggests greater leaching potential at Baturraden.

Chloride concentrations also diverge sharply: Baturraden contains 724–754 mg/L, far exceeding Guci's 17.3–44.2 mg/L [2]. Given that chloride forms stable REE complexes at high temperatures [13], Baturraden offers more favorable conditions for chloride-mediated transport. Anion composition further differentiates the systems; Baturraden is sulfate–chloride–bicarbonate type, whereas Guci is bicarbonate-dominated [2]. Acid–sulfate waters are typically REE-rich, and high bicarbonate levels at both sites, especially in Baturraden's travertine-bearing areas, likely reflect volcanic CO_2 condensation or subsurface carbonate dissolution. CO_2 can also enhance REE mobility [21].

Overall, these contrasting geochemical parameters, such as temperature, pH, and ligand composition, indicate that Baturraden possesses a more conducive geochemical environment for REE mobilization and transport compared to Guci. However, both systems exhibit features favorable to REE enrichment.

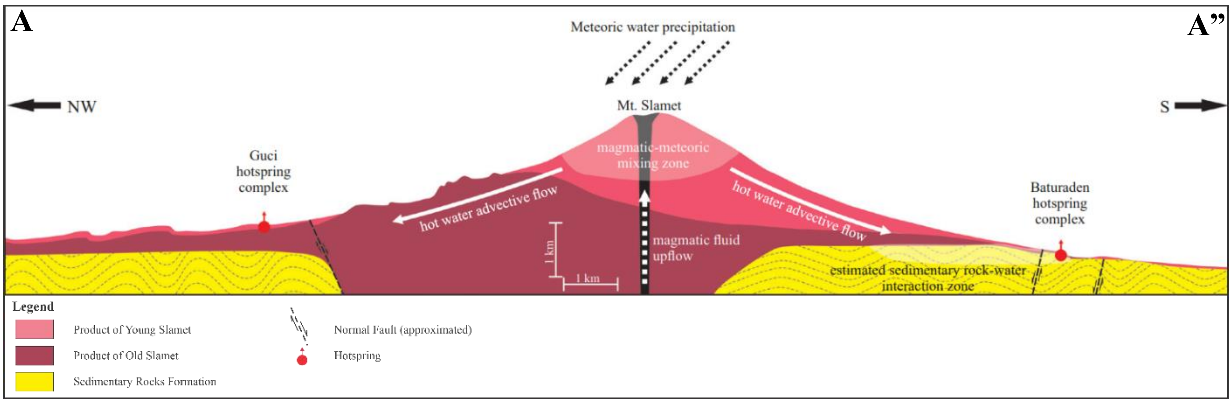

Figure 2. The modification of the subsurface section of the hydrogeological system along Guci-Slamet Summit-Baturraden, as shown in Figure 1 [18], reveals the geothermal manifestation of the Baturraden area, which is influenced by the sedimentary rock formations beneath it. In contrast, the Guci area is influenced by meteoric water, which affects the type of geothermal fluid

Comparison of Guci (Acid-Vapor Side) vs. Baturraden (Formation Water Mixed Side)

The contrasting geochemical signatures of Guci and Baturraden fluids reflect divergent fluid pathways and water-rock interaction processes (Table 3). These differences imply that Baturraden may have a greater REEs transport capacity with its lower pH and higher chloride concentration than Guci. Guci fluids, which are more bicarbonate-dominated and diluted with meteoric water, may experience more rapid REEs precipitation due to carbonate complexation and adsorption at higher pH.

Table 3. Comparison between Guci and Baturraden based on geochemical signatures

Guci (Acid-Vapor Side / Fumarole Condensate)	**Baturraden (Formation Water Mixture Side)**
Guci fluids have characteristics similar to fumarole condensate water from the summit of Mount Slamet that has been diluted by meteoric water [2].	Baturraden fluids show the influence of fumarole condensate and formation water contributions from marine sedimentary rocks [2]. The most likely mechanism is the involvement of marine sedimentary rocks beneath Mount Slamet in the water-rock interaction process.
The water is dominated by bicarbonate type with low chloride concentration (17.3–44.2 mg/L) and high boron concentration (2.84–6.87 mg/L) [2].	The water is classified as sulfate-chloride-bicarbonate with very high chloride concentrations (724–754 mg/L) and lower boron concentrations (3.97–4.40 mg/L) than Guci. The Cl/B ratio in Baturraden is similar to seawater's, supporting the formation of water input [2].
The pH of the fluid tends to be neutral to slightly alkaline (pH 8) [2].	The pH of the fluid tends to be neutral to slightly acidic (pH 6-7) [2].
Thin travertine deposits are observed in Guci [2].	Thick and prominent travertine deposits are found in Pancuran Pitu, Baturraden, indicating bicarbonate-rich fluids [2].
The wall rocks in Guci are volcanic rock products of Mount Slamet [2].	The wall rocks in Baturraden are also products of volcanic rocks from Mount Slamet [2].

REEs Pattern Projection Based on Geochemical Data

Based on the available geochemical data and general understanding of REEs behavior in geothermal systems, Baturraden fluids, with their lower pH (6–7) and much higher chloride concentrations, will likely exhibit higher total REEs concentrations than Guci fluids (pH 8) [2]. REEs fluid concentrations are generally inversely proportional to pH [10], [13].

Given that the host rocks at Slamet are basalt and andesite-basaltic, which are calc-alkaline igneous rocks [3], the chondrite-normalized REEs patterns will likely exhibit LREE enrichment, as is often seen in arc volcanic rocks [3], [15], [22]. Although the surface manifestation temperatures in Baturraden and Guci do not reach the 250°C usually associated with strong positive Eu anomalies, the potential for positive Eu anomalies in deep reservoir fluids cannot be ruled out if the high temperature (>250°C) and strong reduction conditions are achieved at depth [23], [24]. Interaction with basaltic source rocks may also contribute to positive Eu anomalies [9], [23], [24]. Cerium anomalies can reflect redox conditions, with negative anomalies indicating oxidation and positive anomalies indicating high carbonate alkalinity. Given that Guci fluids are bicarbonate-rich and Baturraden has large travertine deposits, the potential for positive Ce anomalies, especially in Guci, should be considered if high carbonate alkalinity conditions are present [8], [24].

Possible REEs Occurrence & Scientific Significance

The presence of REEs in geothermal areas in Indonesia is related to hydrothermal activity along the magmatic zone, where REEs can be trapped in clay and produce high-level deposits through weathering processes and hydrothermal activity [8]. Although REEs concentrations in geothermal fluids are generally low, they can exceed REEs concentrations in the ocean by up to 1,000 times [25].

The scientific significance of the presence of REEs in the geothermal fluids of Mount Slamet is enormous, apart from the economic potential. REEs are a sensitive index of crystal-liquid equilibrium and water-rock interactions in geological systems. REEs studies can help reveal complex geological processes and Earth history [12], [26]. REEs patterns can provide information about fluid sources (e.g., source rocks, meteoric water, seawater/formation) and their migration pathways [5], [10]. Eu and Ce anomalies can serve as indicators of physicochemical conditions (temperature, redox) in the reservoir [10], [24]. REEs geochemistry in geothermal systems can provide insight into the behavior of actinides (e.g., Pu^{3+}, Am^{3+}) if nuclear waste is stored in geological formations [12]. Research on REEs in active geothermal systems in Indonesia is still lacking compared to other geothermally rich countries, partly due to data confidentiality. Therefore, any REEs study in Slamet will significantly increase scientific knowledge about geothermal systems in Indonesia and provide more complete information for the management and development of geothermal and renewable energy [27], [28].

CONCLUSION

The geothermal system of Mount Slamet, particularly at Baturraden and Guci, exhibits geochemical and hydrogeochemical characteristics indicative of potential REEs mobilization and enrichment. Although direct measurements of REEs concentrations in these manifestations are currently unavailable, regional magmatic context and analogies from global geothermal systems underscore the area's significance as a prospective REEs-bearing environment. This study contributes a conceptual framework that links surface fluid characteristics with underlying geochemical mechanisms controlling REEs behavior in volcanic geothermal systems, representing a novel approach in the context of Indonesian geothermal research.

Several geochemical indicators support this potential. Baturraden hot springs exhibit pH values of 6–7, more acidic than Guci (pH ~8). Acidic fluids enhance metal leaching and are generally associated with higher REEs solubility. Baturraden fluids contain elevated Cl levels (724–754 mg/L), favoring the formation of REEs-chloride complexes that are stable under high-temperature conditions and facilitate REEs transport. Both sites are rich in bicarbonate ions, likely sourced from volcanic CO_2 or limestone dissolution at depth, which can enhance REEs mobility in hydrothermal fluids. Interaction with both volcanic and marine sedimentary rocks, especially in Baturraden area, contributes to diverse sources for REEs leaching and highlights the complexity of subsurface processes.

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FUTURE WORK RECOMMENDATION

Given the promising geochemical indicators identified, future research should prioritize direct sampling and quantitative analysis of REEs concentrations in geothermal fluids and associated travertine deposits. Advanced techniques such as Nd–Sm isotopic analysis, sequential leaching, and REEs adsorption–desorption experiments on carbonate sinter and alteration minerals are recommended to clarify REEs sources, pathways, and retention mechanisms. A site-specific geochemical modeling approach may also aid in predicting the behavior of subsurface REEs. These efforts will not only validate conceptual models developed in this study but also support the strategic development of Indonesia's critical mineral resources in alignment with national clean energy and mineral diversification goals.

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