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Rare Earth Elements: Bridging the Gap between Inorganic Chemistry and Geology

[1]Khlieeq Ul Zaman, [2]Saima Batool, [3]Rani Ummay Farwa, [4]Aflah Jahan, [5]Muhammad Bilal
[1]Student, [2]Student, [3]Student, [4]Student, [5]Student
[1]Department of Earth Sciences,
[1]University of Sargodha, Sargodha, Pakistan

Abstract : The 17 chemically related elements known as rare earth elements (REEs) have special characteristics and are used in a variety of products, including electronics, magnets, and catalysis. As these elements are often found in many geological contexts and their distribution and behavior in natural systems are impacted by their complicated chemistry, there has been an increase in interest in the relationship between REEs and geology in recent years. This study intends to investigate the interplay between inorganic chemistry and geology in the context of rare earth elements, including their presence in geologic materials, speciation, and behavior in natural systems, as well as their interactions with other elements and minerals. This paper also emphasizes the value of interdisciplinary study and cooperation between inorganic chemists and geologists in expanding our comprehension of the function of rare earth elements in Earth's geology and their consequences for environmental and financial issues.

***Index Terms* - Rare earth elements, inorganic chemistry, geology, speciation, minerals, and interdisciplinary research.**

I. INTRODUCTION

Rare Earth Elements (REEs) represent a cohort of 17 chemically analogous elements that have attracted substantial scientific and industrial scrutiny, primarily attributed to their distinctive characteristics and extensive utility across diverse high-technology sectors (Mwewa et al., 2022). Among the constituents of REEs are notables such as lanthanum (La), cerium (Ce), neodymium (Nd), and yttrium (Y), among others. The indispensability of these elements manifests in their pivotal roles within contemporary technological paradigms encompassing electronics, renewable energy infrastructures, defense systems, and healthcare innovations (Haque et al., 2014).

The burgeoning significance of Rare Earth Elements (REEs) across diverse applications has sparked an escalating scientific curiosity, necessitating an intensified inquiry into their geochemical proclivities and spatial allocation within the Earth's lithosphere, as expounded by Migaszewski et al. in 2015. Geology assumes pivotal import in elucidating the genesis, spatial dissemination, and accessibility of REEs, given their preeminent provenance from mineral reservoirs embedded within the terrestrial crust. Consequently, the study of REEs mandates a holistic, interdisciplinary approach to surmount the schism that separates the realms of inorganic chemistry and geological sciences, as underscored by the insights imparted by Arienzo et al. in 2022.

In recent years, there has been a growing focus on the nexus between Rare Earth Elements (REEs) and geological phenomena. This heightened interest stems from the recognition that a comprehensive comprehension of the geological mechanisms governing the presence and dispersion of REEs is of paramount importance in fostering their enduring procurement and utilization (Khan et al., 2017). The investigation and retrieval of REEs routinely entail intricate geological and geochemical procedures, encompassing processes such as weathering, erosion, sedimentary deposition, and metamorphism, all of which exert profound influence upon the concentration and dispersion patterns of REEs across diverse geological settings (Landim et al., 2022).

This paper endeavors to elucidate the interrelationship between the realm of inorganic chemistry and the geological domain within the specific context of Rare Earth Elements (REEs). Our objective is to underscore the profound import of REEs across a myriad of applications and their burgeoning significance in contemporary technological advancements. Furthermore, we intend to delve into the escalating scholarly intrigue surrounding the elucidation of geochemical comportment and distribution patterns exhibited by REEs within the Earth's lithospheric framework. We shall elucidate the pivotal role played by geological processes in the origination, dispersal, and accessibility of these elemental entities.

Employing a multidisciplinary approach that seamlessly amalgamates tenets from the realms of inorganic chemistry and geology, this manuscript aspires to furnish discernment into the intricacies governing the dynamic interplay between REEs and geogenic phenomena. Our overarching goal is to impart insights into the intricate interactions involving REEs and geological mechanisms and, in turn, elucidate their ramifications for the sustainable extraction and utilization of these pivotal constituents.

II. SIGNIFICANCE OF REES

REEs have unique properties that make them essential in a wide range of modern technologies and applications, and their increasing importance in geology and inorganic chemistry has significant implications for various industries and the global economy.

Electronics:

Rare earth elements (REEs) play a pivotal role in the manufacturing of electronic devices, encompassing smartphones, computers, televisions, as well as emerging sustainable energy technologies like wind turbines and electric vehicle propulsion systems (Duchna et al., 2022). The indispensability of REEs stems from their exceptional magnetic attributes, electrical conductive capabilities, and luminescent characteristics, rendering them indispensable constituents in the fabrication of magnets, phosphors, and capacitors (Binnemans et al., 2018).

Clean Energy:

Rare earth elements (REEs) are pivotal components in facilitating the shift towards clean energy technologies. Notably, neodymium and dysprosium, both classified as REEs, hold indispensable significance in the manufacture of high-performance magnets deployed in wind turbines and electric vehicles. These magnets, by virtue of their REE composition, are instrumental in enhancing energy generation and storage efficiency (Gielen & Lyons, 2022).

Defense and Aerospace:

Rare earth elements (REEs) play a pivotal role in defense and aerospace endeavors, encompassing applications such as guided missile systems, radar systems, and aircraft engines. They find essential utility in the fabrication of lightweight, high-strength materials, lasers, and nocturnal vision enhancement apparatus, thereby establishing their irreplaceable significance in contemporary defense and aerospace technologies (Pavel et al., 2016).

Medical Technologies:

Rare earth elements (REEs) find application in a multitude of medical technologies, encompassing magnetic resonance imaging (MRI) apparatus, X-ray and computed tomography (CT) scan detectors, as well as pharmaceuticals employed in cancer treatment. These deployments of REEs are predicated upon their distinctive attributes, such as magnetic, luminescent, and radiopaque properties, which bestow them with the capacity to facilitate precise diagnostic procedures and therapeutic interventions (Skuldt 2001).

Consumer Electronics:

Rare earth elements (REEs) find extensive applications in diverse consumer electronic devices such as smartphones, tablets, cameras, and televisions, owing to their distinctive luminescent characteristics and capacity to engender vivid coloration within display technologies, as elucidated by Deshmane et al. in 2019.

Environmental Remediation:

Rare earth elements (REEs) find application in environmental remediation methodologies, including wastewater treatment and soil reclamation, with the primary purpose of eliminating deleterious substances and pollutants from the natural milieu. REEs exhibit a notable capacity for adsorbing heavy metals and diverse contaminants, thereby rendering them efficacious agents for environmental amelioration endeavors (Verma, 2021).

The escalating significance of Rare Earth Elements (REEs) within contemporary technological paradigms carries profound ramifications for the fields of geology and inorganic chemistry. From a geological perspective, REEs are commonly encountered in intricate mineral deposits characterized by low concentrations, thereby rendering their retrieval a formidable and economically burdensome endeavor (Yang et al., 2013). A comprehensive comprehension of the geochemical and geological mechanisms governing the genesis and dispersion of REE reservoirs stands as an imperative prerequisite for the streamlined pursuit of resource prospecting and extraction endeavors. In parallel, inorganic chemistry assumes a pivotal role in the evolution of cutting-edge materials and technologies reliant upon REEs, encompassing the synthesis of REE compounds fine-tuned to exhibit bespoke attributes tailored for specific applications (Balaram, 2019).

Usage of Rare Earth Elements (REE) in Emerging technologies

Application	Examples
Lightweight Magnets	Cars, Electronics, wind turbine, Speakers
Catalyst	Automotive catalyst, clean diesel, oil refining
Catalyst	Electric Motors, Generators, Hybrid Batteries
Polishing Powders	TV, computer screens, plasma, CRT, optical lenses
Glass additive	CRT, small optical lenses, phosphor, TV and computer

III. THE INTEREST OF THE RESEARCHER IN REES

A burgeoning scholarly concern has emerged within the scientific community, particularly among geologists, pertaining to the comprehension of the geochemical dynamics and spatial dispersion of Rare Earth Elements (REEs) within the terrestrial lithosphere. This heightened attention stems from the pivotal role that geological processes assume in the origination, spatial dissemination, and accessibility of these constituent elements. Numerous determinant factors underlie the upsurge in this scholarly engagement:

Economic Importance:

The escalating requisition for Rare Earth Elements (REEs) across diverse technological and application domains has elicited an augmented fascination in comprehending their spatial allocation within the terrestrial lithosphere (Hein et al., 2013). REEs assume pivotal roles as constituents within numerous advanced and environmentally sustainable technologies, thereby conferring pronounced ramifications upon worldwide supply networks and economic frameworks (Golev et al., 2014). Consequently, a profound grasp of the geological mechanisms underpinning the manifestation and dispersion of REEs becomes imperative, enjoining the assurance of an unwavering provision of these constituents to facilitate forthcoming technological progressions.

Complex Geochemical Behavior:

Rare earth elements (REEs) manifest intricate and distinctive geochemical characteristics, thereby confounding the comprehension of their spatial disposition within the Earth's lithosphere. Their akin chemical attributes engender their co-occurrence within mineral matrices, imparting a formidable challenge to their isolation and recovery (Balaram, 2019). Furthermore, REEs exhibit divergent chemical propensities across disparate geological processes encompassing weathering, erosion, transport, and mineralization. These processes give rise to a spectrum of distribution patterns for REEs (Bao & Zhao 2008). Consequently, investigating the geochemical dynamics of REEs within distinct geological contexts offers valuable insights into the mechanisms governing their mobility, aggregation, and concentration, which are pivotal for the identification of prospective REE reservoirs.

Geological Controls:

Geology assumes a pivotal role in the genesis, dispersion, and accessibility of Rare Earth Elements (REEs). REE accumulations are conventionally affiliated with distinct geological contexts, encompassing igneous formations, carbonatitic occurrences, alkaline complexes, and hydrothermal regimes, as delineated by Wang et al. in 2020. The geological mechanisms governing these phenomena, notably magmatic differentiation, hydrothermal modification, and weathering processes, may culminate in the aggregation and augmentation of REEs within specific mineralogical or lithological substrates, as expounded upon by Bern et al. in 2017. Consequently, a comprehensive comprehension of the geological determinants governing the manifestation of REEs can be instrumental in discerning regions of promise for exploration and exploitation endeavors.

Future Resource Potential:

Given the burgeoning demand for Rare Earth Elements (REEs) juxtaposed with the finite supply of established high-grade reserves, an imperative arises to delve into novel reservoirs for REEs. This necessitates the examination of atypical sources, encompassing mine tailings, coal ash, and various industrial byproducts, in addition to the uncharted territories of deep-sea deposits and analogous unexplored domains, as postulated by Peiravi et al. in 2021. Profound comprehension of the geologic mechanisms underpinning the genesis and dispersion of REEs offers a pivotal insight into the recognition of prospective resource reservoirs and the formulation of strategies for prospective REE prospecting and extraction, as articulated by Charles et al. in 2013.

IV. OCCURRENCE OF REES IN GEOLOGIC MATERIALS

Distribution of REEs in the Earth's Crust:

REEs are relatively abundant in the Earth's crust, with average crustal abundances ranging from 0.3 to 60 parts per million (ppm). However, they are considered "rare" due to their low concentration compared to other more commonly occurring elements (Lusty & Walter, 2010). The distribution of REEs in the Earth's crust is not uniform and varies geographically. The highest concentrations of REEs are typically found in areas with igneous and metamorphic rocks, such as carbonatites, alkaline complexes, and rare-metal granites (Smith et al., 2016). The global distribution of their occurrences on each continent is depicted in Figure 1.

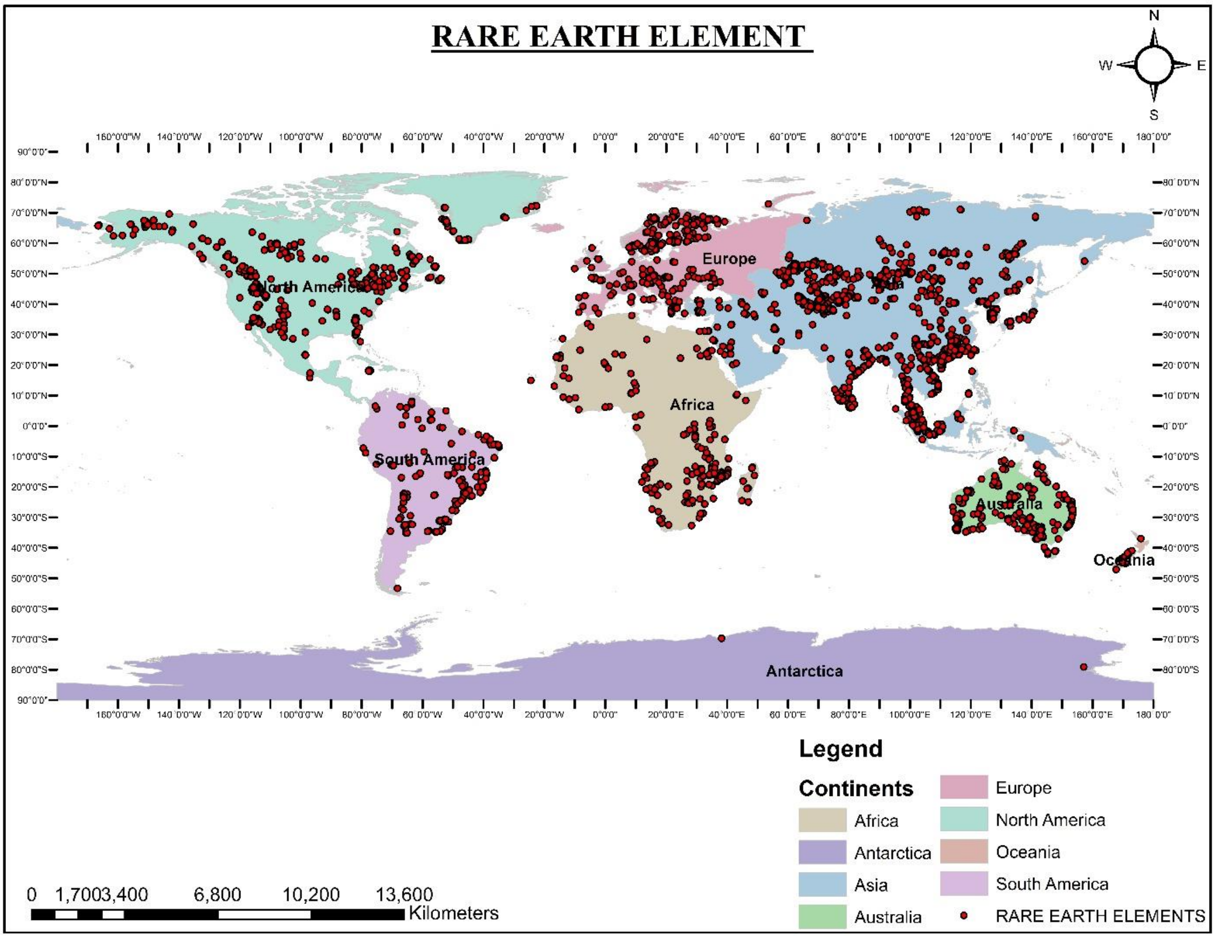

Fig. 1: Map showing the occurrence of REEs in the world

Occurrence of REEs in Different Types of Geologic Materials:

REEs can occur in various geologic materials, including ores, minerals, rocks, and sediments. REEs are often found in association with other elements, forming complex minerals and ores (Ram et al., 2019). Some of the common minerals that host REEs include bastnäsite, monazite, xenotime, and apatite. These minerals can be found in different types of rocks, such as carbonatites, alkaline rocks, granite, and phosphate rocks (Dostal, 2017). Sediments, including marine and lacustrine sediments, can also contain significant concentrations of REEs, which are typically associated with clay minerals and organic matter (Bai et al., 2015).

Geological Processes and Factors Influencing Concentration, Mobility, and Availability of REEs:

The concentration, mobility, and availability of REEs in natural systems are influenced by various geological processes and factors. These include magmatic processes, hydrothermal processes, weathering, erosion, sedimentation, diagenesis, metamorphism, and tectonic activity (Bekker et al., 2010). Magmatic processes, such as fractional crystallization and partial melting of magmas, can lead to the concentration of REEs in certain types of igneous rocks, such as carbonatites and alkaline complexes (Verplanck, et al., 2011). Hydrothermal processes, involving hot fluids that circulate through rocks, can also play a significant role in the concentration of REEs in ore deposits (Barnes, 1997). Weathering and erosion of rocks can release REEs into the environment and transport them to sedimentary basins, where they can become incorporated into sediments during sedimentation (Large et al., 2017).

Diagenesis, which refers to the physical and chemical changes that occur in sediments during burial and compaction, can influence the mobility and availability of REEs in sedimentary rocks (Milodowski et al., 1991). Metamorphism, which involves changes in temperature and pressure in rocks, can also affect the concentration and distribution of REEs (Konrad et al., 2008). Tectonic activity, including faulting and folding, can cause geological materials to be transported and redistributed, leading to the formation of REE deposits in certain regions (Berger et al., 2013). The availability of REEs in natural systems can also be influenced by factors such as pH, redox conditions, and the presence of ligands in the environment, which can affect their solubility, mobility, and bioavailability (Violante et al., 2010). The distribution of Rare Earth Elements (REEs) along geological features is illustrated in Figure 2.

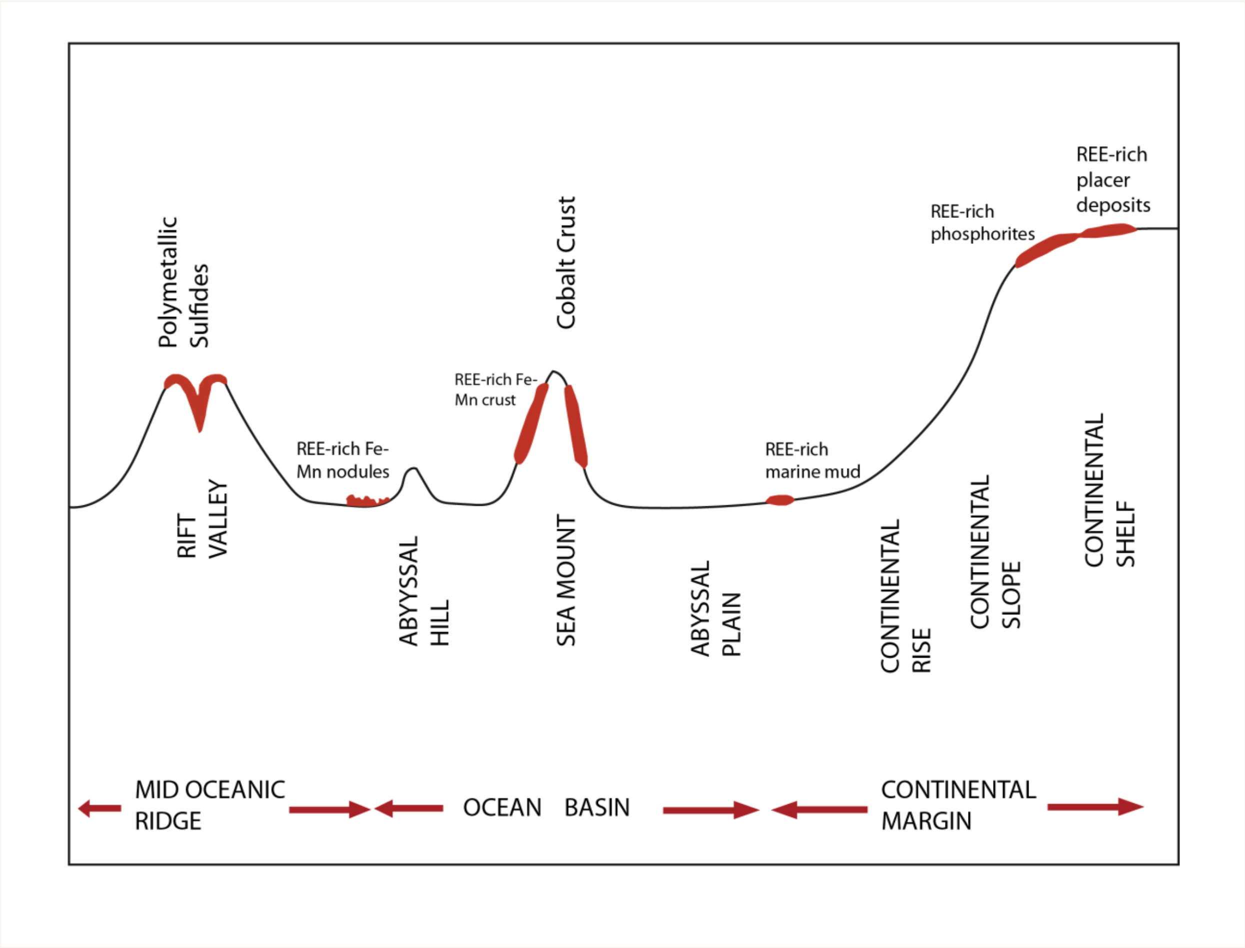

Fig. 2: Figure showing the occurrence of REEs along the geological features (V. Balaram- Vol. 10, 2019)

V. SPECIATION AND BEHAVIOR OF REES IN NATURAL SYSTEMS

The complex chemistry of REEs arises from their unique electronic configuration and the presence of f-electrons, which makes their oxidation states and coordination chemistry highly variable in natural environments (Atwood, 2013). REEs can exist in different oxidation states, ranging from +2 to +4, with +3 being the most stable and predominant oxidation state in natural systems (Konecke et al., 2017). The oxidation state of REEs affects their reactivity, solubility, and complexation behavior. For example, under oxidizing conditions, REEs tend to form more soluble species in aqueous solutions, while under reducing conditions, they can precipitate or form less soluble species (Smrzka et al., 2019).

The coordination chemistry of REEs is also complex and depends on factors such as pH, temperature, and the presence of ligands (ions or molecules that can bind to a metal ion) (Götzkeet al., 2019). REEs can form various coordination complexes with different ligands, such as hydroxide (OH-), carbonate (CO32-), sulfate (SO42-), and organic ligands (Cetiner & Xiong, 2008). The stability and formation of these complexes affect the speciation and mobility of REEs in natural systems. Complexation reactions involving REEs are crucial in controlling their behavior in natural environments. REEs can form strong complexes with ligands, which can affect their solubility, mobility, and fate (Violante et al., 2010). For example, in aqueous solutions, REEs can form soluble complexes with organic ligands and be transported in solution. In soils and sediments, REEs can adsorb onto mineral surfaces or form precipitates with other elements, which can control their mobility and bioavailability (Smrzka et al., 2019).

The speciation and behavior of REEs in different environmental conditions are influenced by various factors such as pH, temperature, redox conditions, mineralogy, and the presence of other ions (Caporale & Violante, 2016). For instance, in acidic environments, REEs tend to be more soluble and mobile, while in alkaline environments, they tend to precipitate or adsorb onto minerals (Bowell et al., 2000). In reducing environments, REEs can form less soluble species and precipitate, while in oxidizing environments, they can form more soluble complexes (Choppin, 2007). The speciation and behavior of REEs in natural systems can influence their transport in surface and groundwater, their bioavailability to organisms, and their potential for contaminating soils and sediments (Khan et al., 2017).

VI. INTERACTIONS OF REES WITH OTHER ELEMENTS AND MINERALS

The interactions of Rare Earth Elements (REEs) with other elements and minerals in geologic materials are complex and can involve various processes such as ion exchange, sorption, precipitation, and redox reactions (Liu et al., 2022). Ion exchange is a common process by which REEs can substitute for other ions in the crystal lattice of minerals (Moldoveanu & Papangelakis, 2016). For example, REEs can replace calcium (Ca) in calcium-bearing minerals like apatite or exchange with other cations in clay minerals. This process depends on factors such as the size and charge of the REE ion, as well as the mineralogy and conditions of the system (Julapong et al., 2023).

Sorption is another important process that can affect the behavior of REEs in geologic materials. REEs can sorb onto the surfaces of minerals and organic matter through processes such as adsorption and chemisorption (Laveuf & Cornu, 2009). Adsorption involves the physical attachment of REEs to the mineral surfaces, while chemisorption involves a chemical reaction between the REEs and the mineral surfaces (Guo et al., 2022). Sorption can be influenced by factors such as pH, temperature, mineralogy, and the presence of other ions, which can affect the surface charge and reactivity of minerals (Harter & Naidu, 2001). Precipitation is a process by which REEs can form solid phases, such as hydroxides, carbonates, or phosphates, under certain conditions. Precipitation can occur due to changes in pH, temperature, or redox conditions, which can cause the REEs to become less soluble and form solid phases (Verplanck, 2017). Precipitation can occur within geologic materials, such as in fractures, pore spaces, or sediments, and can influence the mobility and fate of REEs in the environment (Duff, 2001).

Redox reactions involving REEs can also play a significant role in their interactions with geologic materials (Smrzka et al., 2019). REEs can exhibit different oxidation states, and their redox reactions can involve changes in their speciation, solubility, and reactivity. For example, under reducing conditions, REEs can form less soluble species, such as hydroxides or sulfides, while under oxidizing conditions, they can form more soluble complexes (Wood & Samson, 2006). The reactivity and mobility of REEs in geological environments are influenced by various factors. pH is a critical factor, as it can affect the speciation and solubility of REEs. In acidic conditions, REEs tend to be more soluble and mobile, while in alkaline conditions, they tend to form less soluble species (Khorasanipour & Jafari, 2008). Temperature can also influence the reactivity of REEs, as higher temperatures can increase the rates of chemical reactions involving REEs (Rees, 1980).

Mineralogy plays a crucial role in the interactions of REEs with geologic materials, as different minerals can have varying affinities for REEs. For example, minerals with high surface areas, such as clays, can have high sorption capacities for REEs, while minerals with low surface areas, such as quartz, may have lower sorption capacities (Yang et al., 2019). Additionally, the presence of organic matter can also influence the interactions of REEs with geologic materials, as organic matter can act as ligands and form complexes with REEs, or influence mineral surface properties (Cumberland et al., 2016). Inorganic chemistry plays a critical role in elucidating the mechanisms and kinetics of REE interactions with geologic materials (Başaran et al., 2021). Studies on the thermodynamics and kinetics of REE reactions with minerals and other elements can provide insights into the mechanisms by which REEs interact with geologic materials, the stability of the formed phases, and the rates at which these interactions occur (Dong et al., 2022).

VII. Importance of Interdisciplinary Research

Interdisciplinary research and collaboration between inorganic chemists and geologists are essential for advancing our understanding of the relationship between REEs and geology. The complex chemistry and behavior of REEs in geologic systems require expertise from both fields to fully comprehend their speciation, reactivity, and mobility in natural environments. Inorganic chemists can contribute to the understanding of REEs in geologic systems by providing insights into the fundamental principles of coordination chemistry, thermodynamics, and kinetics of REE reactions with minerals and other elements. Inorganic chemists can also develop analytical techniques, such as spectroscopy, chromatography, and electrochemistry that can be applied to study REEs in geologic materials. These techniques can provide valuable information about the speciation and behavior of REEs in different environmental conditions.

Geologists, on the other hand, bring their expertise in field observations, sample collection, and geologic processes to contextualize the behavior of REEs in natural systems. They can provide insights into the geological settings where REEs are found, the mineralogy and geochemistry of the host rocks, and the processes that control the mobility and fate of REEs in geologic materials. Geologists can also contribute to understanding the geological history of REEs, their distribution patterns, and their potential economic resources. Integrated research approaches and techniques from both fields can provide a comprehensive understanding of the speciation and behavior of REEs in geologic systems. For example, field studies that involve sample collection and characterization can be combined with inorganic chemistry techniques, such as X-ray spectroscopy, to identify the mineral phases hosting REEs and their oxidation states. Laboratory experiments that investigate the sorption or precipitation of REEs onto minerals can be combined with thermodynamic modeling to predict the speciation and solubility of REEs under different environmental conditions.

The implications of REEs in geology have significant environmental, economic, and societal considerations. REEs are critical components of many modern technologies, including electronics, energy systems, and transportation. Understanding the distribution, behavior, and potential economic resources of REEs in geologic materials can have implications for resource exploration and extraction, as well as environmental impact assessments. Moreover, the mobility and fate of REEs in natural systems can also have environmental implications, as they can potentially impact ecosystems and water quality.

VIII. Conclusion

In conclusion, the study of Rare Earth Elements (REEs) represents a fascinating intersection of inorganic chemistry and geology. REEs exhibit a complex chemistry with a wide range of oxidation states, coordination behaviors, and interactions with geologic materials. Understanding their speciation and behavior in natural systems is pivotal for a myriad of applications, from resource exploration and extraction to environmental impact assessments.

"Rare Earth Elements: Bridging the Gap between Inorganic Chemistry and Geology" underscores the paramount importance of interdisciplinary research and collaboration between inorganic chemists and geologists. Inorganic chemistry provides the foundational principles, analytical tools, and expertise necessary to elucidate the fundamental mechanisms governing REE interactions with minerals and other elements. Meanwhile, geologists contribute their knowledge of geological settings, field observations, and the intricate processes influencing REE mobility and distribution in the Earth's crust.

Integrated research approaches, encompassing field studies, laboratory experiments, and sophisticated analytical techniques, hold the key to unlocking the secrets of REEs in geologic systems. From identifying host minerals and oxidation states to predicting speciation and solubility under diverse environmental conditions, this collaborative effort leads to a comprehensive understanding of REEs' intricate role in Earth's geological processes.

The implications of REEs in geology extend far beyond scientific curiosity. With their integral role in modern technologies and the burgeoning demand for sustainable energy solutions, REEs have significant economic and industrial relevance. Moreover, as REE mobility within geologic systems can potentially impact ecosystems and water quality, the environmental consequences of REE behavior are paramount.

As we navigate the complexities of the modern world, "Rare Earth Elements: Bridging the Gap between Inorganic Chemistry and Geology" serves as a clarion call for continued interdisciplinary research, aiming to unveil the mysteries of these remarkable elements and harness their potential for both scientific advancement and responsible resource management. The fusion of inorganic chemistry and geology stands as a testament to the power of collaboration in our pursuit of knowledge and solutions for a sustainable future.

REFERENCES

1. Arienzo, M., Ferrara, L., Trifuoggi, M., & Toscanesi, M. (2022). Advances in the fate of rare earth elements, REE, in transitional environments: Coasts and estuaries. *Water*, *14*(3), 401.
2. Atwood, D. A. (Ed.). (2013). *The rare earth elements: fundamentals and applications*. John Wiley & Sons.
3. Bai, Y., Liu, Z., Sun, P., Liu, R., Hu, X., Zhao, H., & Xu, Y. (2015). Rare earth and major element geochemistry of Eocene fine-grained sediments in oil shale-and coal-bearing layers of the Meihe Basin, Northeast China. *Journal of Asian Earth Sciences*, *97*, 89-101.
4. Balaram, V. (2019). Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers*, *10*(4), 1285-1303.
5. Balaram, V. (2019). Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers*, *10*(4), 1285-1303.
6. Bao, Z., & Zhao, Z. (2008). Geochemistry of mineralization with exchangeable REY in the weathering crusts of granitic rocks in South China. *Ore Geology Reviews*, *33*(3-4), 519-535.
7. Barnes, H. L. (Ed.). (1997). *Geochemistry of hydrothermal ore deposits*. John Wiley & Sons.
8. Başaran, K., Topçubaşı, B. U., & Davran-Candan, T. (2021). Theoretical investigation of CO2 adsorption mechanism over amine-functionalized mesoporous silica. Journal of CO2 Utilization, 47, 101492.
9. Bekker, A., Slack, J. F., Planavsky, N., Krapez, B., Hofmann, A., Konhauser, K. O., & Rouxel, O. J. (2010). Iron formation: the sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric processes. *Economic Geology*, *105*(3), 467-508.
10. Berger, A., Gnos, E., Janots, E., Whitehouse, M., Soom, M., Frei, R., & Waight, T. E. (2013). Dating brittle tectonic movements with cleft monazite: Fluid-rock interaction and formation of REE minerals. *Tectonics*, *32*(5), 1176-1189.
11. Bern, C. R., Yesavage, T., & Foley, N. K. (2017). Ion-adsorption REEs in regolith of the Liberty Hill pluton, South Carolina, USA: An effect of hydrothermal alteration. *Journal of Geochemical Exploration*, *172*, 29-40.
12. Binnemans, K., Jones, P. T., Müller, T., & Yurramendi, L. (2018). Rare earths and the balance problem: how to deal with changing markets?. *Journal of Sustainable Metallurgy*, *4*, 126-146.
13. Bowell, R. J., Rees, S. B., & Parshley, J. V. (2000). Geochemical predictions of metal leaching and acid generation: geologic controls and baseline assessment. Geology and ore deposits, 799-823.
14. Brown Jr, G. E., Foster, A. L., & Ostergren, J. D. (1999). Mineral surfaces and bioavailability of heavy metals: a molecular-scale perspective. Proceedings of the National Academy of Sciences, 96(7), 3388-3395.
15. Caporale, A. G., & Violante, A. (2016). Chemical processes affecting the mobility of heavy metals and metalloids in soil environments. Current Pollution Reports, 2, 15-27.
16. Cetiner, Z. S., & Xiong, Y. (2008). Chemical controls on the solubility, speciation and mobility of lanthanum at near surface conditions: a geochemical modeling study. Applied geochemistry, 23(8), 2301-2315.
17. Charles, N., Tuduri, J., Guyonnet, D., Melleton, J., & Pourret, O. (2013, August). Rare earth elements in Europe and Greenland: a geological potential? An overview. In *12th meeting of the Society of Geology Applied to Mineral Deposits (SGA)* (Vol. 201, pp. 1698-1701).
18. Choppin, G. (2007). Actinide speciation in the environment. Journal of Radioanalytical and Nuclear Chemistry, 273(3), 695-703.
19. Cumberland, S. A., Douglas, G., Grice, K., & Moreau, J. W. (2016). Uranium mobility in organic matter-rich sediments: A review of geological and geochemical processes. Earth-Science Reviews, 159, 160-185.
20. Davranche, M., Gruau, G., Dia, A., Marsac, R., Pédrot, M., & Pourret, O. (2015). Biogeochemical factors affecting rare earth element distribution in shallow wetland groundwater. *Aquatic geochemistry*, *21*, 197-215.

21. Deblonde, G. J. P., Mattocks, J. A., Park, D. M., Reed, D. W., Cotruvo Jr, J. A., & Jiao, Y. (2020). Selective and efficient biomacromolecular extraction of rare-earth elements using lanmodulin. *Inorganic chemistry*, *59*(17), 11855-11867.
22. Deshmane, V. G., Islam, S. Z., & Bhave, R. R. (2019). Selective recovery of rare earth elements from a wide range of e-waste and process scalability of membrane solvent extraction. *Environmental Science & Technology*, *54*(1), 550-558.
23. Dong, H., Huang, L., Zhao, L., Zeng, Q., Liu, X., Sheng, Y., ... & Chen, H. (2022). A critical review of mineral–microbe interaction and co-evolution: mechanisms and applications. National science review, 9(10), nwac128.
24. Dostal, J. (2017). Rare earth element deposits of alkaline igneous rocks. *Resources*, *6*(3), 34.
25. Duchna, M., & Cieślik, I. (2022). Rare Earth Elements in New Advanced Engineering Applications.
26. Duff, M. C. (2001). Speciation and transformations of sorbed Pu on geologic materials: wet chemical and spectroscopic observations. In Radioactivity in the Environment (Vol. 1, pp. 139-157). Elsevier.
27. Gielen, D., & Lyons, M. (2022). Critical materials for the energy transition: Rare earth elements. *International Renewable Energy Agency: Abu Dhabi, United Arab Emirates*, *48*.
28. Golev, A., Scott, M., Erskine, P. D., Ali, S. H., & Ballantyne, G. R. (2014). Rare earths supply chains: Current status, constraints and opportunities. *Resources Policy*, *41*, 52-59.
29. Götzke, L., Schaper, G., März, J., Kaden, P., Huittinen, N., Stumpf, T., ... & Weigand, J. J. (2019). Coordination chemistry of f-block metal ions with ligands bearing bio-relevant functional groups. Coordination Chemistry Reviews, 386, 267-309.
30. Guo, C., Hou, S., Wang, W., & Jin, H. (2022). Surface chemistry of xanthan gum interactions with bastnaesite and fluorite during flotation. *Minerals Engineering*, *189*, 107891.
31. Haque, N., Hughes, A., Lim, S., & Vernon, C. (2014). Rare earth elements: Overview of mining, mineralogy, uses, sustainability and environmental impact. *Resources*, *3*(4), 614-635.
32. Harter, R. D., & Naidu, R. (2001). An assessment of environmental and solution parameter impact on trace-metal sorption by soils. Soil Science Society of America Journal, 65(3), 597-612.
33. Hein, J. R., Mizell, K., Koschinsky, A., & Conrad, T. A. (2013). Deep-ocean mineral deposits as a source of critical metals for high-and green-technology applications: Comparison with land-based resources. *Ore Geology Reviews*, *51*, 1-14.
34. Julapong, P., Numprasanthai, A., Tangwattananukul, L., Juntarasakul, O., Srichonphaisarn, P., Aikawa, K., ... & Phengsaart, T. (2023). Rare Earth Elements Recovery from Primary and Secondary Resources Using Flotation: A Systematic Review. Applied Sciences, 13(14), 8364.
35. Khan, A. M., Bakar, N. K. A., Bakar, A. F. A., & Ashraf, M. A. (2017). Chemical speciation and bioavailability of rare earth elements (REEs) in the ecosystem: a review. *Environmental Science and Pollution Research*, *24*, 22764-22789.
36. Khan, A. M., Bakar, N. K. A., Bakar, A. F. A., & Ashraf, M. A. (2017). Chemical speciation and bioavailability of rare earth elements (REEs) in the ecosystem: a review. Environmental Science and Pollution Research, 24, 22764-22789.
37. Khorasanipour, M., & Jafari, Z. (2018). Environmental geochemistry of rare earth elements in Cu-porphyry mine tailings in the semiarid climate conditions of Sarcheshmeh mine in southeastern Iran. Chemical Geology, 477, 58-72.
38. Konecke, B. A., Fiege, A., Simon, A. C., Parat, F., & Stechern, A. (2017). Co-variability of $S6+$, $S4+$, and $S2-$ in apatite as a function of oxidation state: Implications for a new oxybarometer. *American Mineralogist*, *102*(3), 548-557.
39. Konrad-Schmolke, M., Zack, T., O'Brien, P. J., & Jacob, D. E. (2008). Combined thermodynamic and rare earth element modelling of garnet growth during subduction: examples from ultrahigh-pressure eclogite of the Western Gneiss Region, Norway. *Earth and Planetary Science Letters*, *272*(1-2), 488-498.
40. Landim, J. S. P., da Silva, Y. J. A. B., do Nascimento, C. W. A., da Silva, Y. J. A. B., Nascimento, R. C., Boechat, C. L., ... & Collins, A. L. (2022). Distribution of rare earth elements in soils of contrasting geological and pedological settings to support human health assessment and environmental policies. *Environmental Geochemistry and Health*, *44*(3), 861-872.
41. Large, R. R., Mukherjee, I., Gregory, D. D., Steadman, J. A., Maslennikov, V. V., & Meffre, S. (2017). Ocean and atmosphere geochemical proxies derived from trace elements in marine pyrite: Implications for ore genesis in sedimentary basins. *Economic Geology*, *112*(2), 423-450.
42. Laveuf, C., & Cornu, S. (2009). A review on the potentiality of rare earth elements to trace pedogenetic processes. Geoderma, 154(1-2), 1-12.
43. Liu, X., Tournassat, C., Grangeon, S., Kalinichev, A. G., Takahashi, Y., & Marques Fernandes, M. (2022). Molecular-level understanding of metal ion retention in clay-rich materials. *Nature Reviews Earth & Environment*, *3*(7), 461-476.
44. Lusty, P., & Walters, A. (2010). Rare earth elements.
45. Migaszewski, Z. M., & Gałuszka, A. (2015). The characteristics, occurrence, and geochemical behavior of rare earth elements in the environment: a review. *Critical reviews in environmental science and technology*, *45*(5), 429-471.
46. Milodowski, A. E., & Zalasiewicz, J. A. (1991). Redistribution of rare earth elements during diagenesis of turbidite/hemipelagite mudrock sequences of Llandovery age from central Wales. *Geological Society, London, Special Publications*, *57*(1), 101-124.
47. Moldoveanu, G. A., & Papangelakis, V. G. (2016). An overview of rare-earth recovery by ion-exchange leaching from ion-adsorption clays of various origins. Mineralogical Magazine, 80(1), 63-76.
48. Mwewa, B., Tadie, M., Ndlovu, S., Simate, G. S., & Matinde, E. (2022). Recovery of rare earth elements from acid mine drainage: a review of the extraction methods. Journal of Environmental Chemical Engineering, 10(3), 107704.
49. Pavel, C. C., & Tzimas, E. (2016). Raw materials in the European defence industry. *European Commission, DG Joint Research Centre, Petten, Netherlands*.
50. Peiravi, M., Dehghani, F., Ackah, L., Baharlouei, A., Godbold, J., Liu, J., ... & Ghosh, T. (2021). A review of rare-earth elements extraction with emphasis on non-conventional sources: Coal and coal byproducts, iron ore tailings, apatite, and phosphate byproducts. *Mining, Metallurgy & Exploration*, *38*, 1-26.

51. Ram, R., Becker, M., Brugger, J., Etschmann, B., Burcher-Jones, C., Howard, D., ... & Petersen, J. (2019). Characterisation of a rare earth element-and zirconium-bearing ion-adsorption clay deposit in Madagascar. *Chemical Geology*, *522*, 93-107.
52. Rees, J. F. (1980). Optimisation of methane production and refuse decomposition in landfills by temperature control. Journal of chemical technology and biotechnology, 30(1), 458-465.
53. Shand, P., Johannesson, K. H., Chudaev, O., Chudaeva, V., & Edmunds, W. M. (2005). *Rare earth element contents of high pCO 2 groundwaters of Primorye, Russia: mineral stability and complexation controls* (pp. 161-186). Springer Netherlands.
54. Skuldt, D. (2001). X-Ray-Based Imaging. *Minimally Invasive Medical Technology. Series: Series in Medical Physics and Biomedical Engineering*, 46-58.
55. Smith, M. P., Moore, K., Kavecsánszki, D., Finch, A. A., Kynicky, J., & Wall, F. (2016). From mantle to critical zone: A review of large and giant sized deposits of the rare earth elements. *Geoscience Frontiers*, *7*(3), 315-334.
56. Smrzka, D., Zwicker, J., Bach, W., Feng, D., Himmler, T., Chen, D., & Peckmann, J. (2019). The behavior of trace elements in seawater, sedimentary pore water, and their incorporation into carbonate minerals: a review. *Facies*, *65*, 1-47.
57. Smrzka, D., Zwicker, J., Bach, W., Feng, D., Himmler, T., Chen, D., & Peckmann, J. (2019). The behavior of trace elements in seawater, sedimentary pore water, and their incorporation into carbonate minerals: a review. *Facies*, *65*, 1-47.
58. Smrzka, D., Zwicker, J., Bach, W., Feng, D., Himmler, T., Chen, D., & Peckmann, J. (2019). The behavior of trace elements in seawater, sedimentary pore water, and their incorporation into carbonate minerals: a review. Facies, 65, 1-47.
59. Smrzka, D., Zwicker, J., Bach, W., Feng, D., Himmler, T., Chen, D., & Peckmann, J. (2019). The behavior of trace elements in seawater, sedimentary pore water, and their incorporation into carbonate minerals: a review. Facies, 65, 1-47.
60. Verma, A. (2021). Bioremediation techniques for soil pollution: An introduction. *Biodegradation technology of organic and inorganic pollutants*.
61. Verplanck, P. L. (2017). The role of fluids in the formation of rare earth element deposits. Procedia Earth and Planetary Science, 17, 758-761.
62. Verplanck, P. L., & Van Gosen, B. S. (2011). *Carbonatite and Alkaline Intrusion-related Rare Earth Element Deposits: A Deposit Model*. US Department of the Interior, US Geological Survey.
63. Violante, A. U. D. N., Cozzolino, V. U. D. N., Perelomov, L. P. S. U., Caporale, A. G., & Pigna, M. U. D. N. (2010). Mobility and bioavailability of heavy metals and metalloids in soil environments. *Journal of soil science and plant nutrition*, *10*(3), 268-292.
64. Violante, A. U. D. N., Cozzolino, V. U. D. N., Perelomov, L. P. S. U., Caporale, A. G., & Pigna, M. U. D. N. (2010). Mobility and bioavailability of heavy metals and metalloids in soil environments. Journal of soil science and plant nutrition, 10(3), 268-292.
65. Wang, Z. Y., Fan, H. R., Zhou, L., Yang, K. F., & She, H. D. (2020). Carbonatite-related REE deposits: An overview. *Minerals*, *10*(11), 965.
66. Wood, S. A., & Samson, I. M. (2006). The aqueous geochemistry of gallium, germanium, indium and scandium. Ore Geology Reviews, 28(1), 57-102.
67. Yang, M., Liang, X., Ma, L., Huang, J., He, H., & Zhu, J. (2019). Adsorption of REEs on kaolinite and halloysite: A link to the REE distribution on clays in the weathering crust of granite. *Chemical Geology*, *525*, 210-217.
68. Yang, X. J., Lin, A., Li, X. L., Wu, Y., Zhou, W., & Chen, Z. (2013). China's ion-adsorption rare earth resources, mining consequences and preservation. *Environmental Development*, *8*, 131-136.