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Exploring Terbium Distribution in Basanite, Monazite and Xenotime: Geological Perspectives and Applications

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Abstract:
Rare earth elements (REEs), particularly terbium, are essential for modern technology, renewable energy, and strategic industries. To obtain this element, it is crucial to explore different rocks and mine it effectively, making the investigation of terbium's geological origins important. Terbium is predominantly found in geological settings such as alkaline igneous rocks, carbonatites, and hydrothermal veins, within minerals like bastnasite, monazite, and xenotime. Its incorporation into these minerals is influenced by magmatic differentiation, hydrothermal alteration, and metamorphic processes. The crystal chemistry of these minerals facilitates terbium's substitution for other REEs due to similar ionic radii and charges, modulated by the geochemical environment during formation. Terbium predominantly exists in the +3 oxidation state, which is more stable and common, whereas the +4 state, found in Tb_4O_7*, is commercially significant. In carbonatite magmas, terbium substitutes for other REEs in bastnasite during crystallization. Monazite forms through magmatic and sedimentary processes, accumulating in igneous, metamorphic, and placer deposits. Xenotime, found in pegmatites and granites, incorporates terbium during high-temperature crystallization and within high-grade metamorphic rocks. Bastnasite and monazite deposits are found in the southern and western parts of India, whereas xenotime deposits are situated in Australia and Sweden. Terbium's magnetic, luminescent, and catalytic properties are indispensable for industrial applications. The absence of terbium would hinder technological progress, limiting advancements towards a sustainable, energy-efficient future. Ensuring a stable terbium supply and adopting responsible resource management practices are essential for sustaining technological innovation and effectively addressing global challenges.*

Keywords: *Terbium, Crystal Chemistry, Bastnasite, Monazite, Xenotime, Geochemical Environment.*

INTRODUCTION

Rare earth elements (REEs) have gathered significant attention in recent years due to their indispensable role in modern technology, renewable energy, and strategic industries (Chen et al., 2023). These elements, comprising a group of 17 chemically similar elements, possess unique properties that make them essential components in a wide array of applications (Gupta and Krishnamurthy, 2016). From magnets in electric vehicles and wind turbines to phosphors in lighting and displays, REEs have become integral to our everyday lives. Among the diverse family of REEs, terbium stands out for its remarkable properties and versatile applications. As one of the lanthanides, terbium boasts magnetic, luminescent, and catalytic properties that are crucial for various industrial sectors (Gschneidner et al., 2016). Its luminescent properties make it a key component in fluorescent lamps, LEDs, and color television tubes, while its magnetic properties find application in high-performance magnets for electronics and clean energy technologies (Xu et al., 2020). Terbium's catalytic activity has implications for green chemistry and environmental remediation (Alomari et al., 2023). Hence, in recent decades, terbium's significance has increased.

Terbium emerged into scientific consciousness in the mid-19th century, amidst the fervor of elemental discovery. In 1843, Swedish chemist Carl Gustaf Mosander unearthed terbium from the mineral cerite, marking its initial recognition. It was not until 1843 that Mosander identified and isolated terbium oxide, laying the foundation for further study. The element owes its name to the village of Ytterby in Sweden, a locality renowned for yielding several rare earth elements, including terbium. Initially found in cerite, a mineral composed of several rare earth elements, terbium's presence was later confirmed in other minerals such as xenotime, gadolinite, and euxenite (Edelmann and Poremba, 1997). These occurrences provided early insights into terbium's geological distribution and its association with other elements within Earth's crust.

Terbium, with its atomic number 65 and atomic weight approximately 158.925 u, places it among the heavier rare earth elements (Edelmann and Poremba, 1997). It exhibits a silvery-white metallic appearance and possesses a high melting point of around 1356°C. Chemically, terbium is reactive, particularly in its trivalent state, forming various compounds with oxygen, sulfur, and other nonmetals. Its electronic configuration, [Xe] $4f^9$ $6s^2$, places it within the lanthanide series, conferring upon its unique chemical characteristics (Edelmann and Poremba, 1997; Hartmut and Leopold, 1986). Terbium shares several common properties with its lanthanide counterparts, including high density, malleability, and ductility. It exhibits paramagnetic behavior, displaying magnetic susceptibility in the presence of an external magnetic field. Terbium compounds often exhibit luminescence, with notable emissions in the green and blue regions of the electromagnetic spectrum. These properties contribute to terbium's versatility in various industrial applications Edelmann and Poremba, 1997; Hartmut and Leopold, 1986.

Terbium, a rare earth element, exhibits variable oxidation states. Terbium (III) refers to terbium in the +3 oxidation state, while terbium (IV) denotes terbium in the +4 oxidation state. Terbium (III) compounds are more stable and commonly encountered, while terbium (IV) compounds are less common but present in Tb_4O_7 (Edelmann and Poremba, 1997; Hartmut and Leopold, 1986). Terbium (III) oxide (Tb_2O_3) is the most common oxide, while terbium (IV) oxide (TbO_2) is less prevalent but commercially significant (Table 1). Terbium (III, IV) oxide (Tb_4O_7), also known as tetraterbium heptaoxide or sometimes as $TbO_{1.75}$, is a compound subject to debate regarding its nature as a discrete compound or a phase in an interstitial oxide system (Table 1). Terbium forms other major oxides, including Tb_2O_3 and Tb_6O_{11} (Edelmann and Poremba, 1997; Hartmut and Leopold, 1986).

This paper investigates terbium's geochemistry, formation, and concentration processes within the Earth's crust, as well as its presence in key minerals such as bastnasite, monazite, and xenotime, using leading examples from India and international. Additionally, the paper explores how terbium is incorporated into these minerals and its diverse applications across various sectors. This study provides a comprehensive understanding of the geological aspects and related properties of terbium in its ore minerals.

Table 1: Oxidation states and Geochemical process of Terbium

Mineral Ore	Composition	Oxidation State of Terbium	Geochemical Process Involved	Reference
Bastnasite	(Ce, La, Nd) $(CO_3)F$	Tb^{3+}	Magmatic differentiation, hydrothermal	Wall and Mariano, 1996; Smith et al., 2000; Chakhmouradian and Wall, 2012
Monazite	(Ce, La, Th) (PO_4, SiO_4)	Tb^{3+}	Magmatic crystallization, metamorphism, placer deposits	Mitchell, 1996; Overstreet, 1967; Mariano and Mariano, 2012
Xenotime	YPO_4	Tb^{3+}	Magmatic crystallization, high-grade metamorphism	Heinrich, 1966; Ni et al., 1995; Imashuku, 2024

GENESIS OF TERBIUM

Terbium is commonly found in association with other rare earth elements (REEs) within specific geological settings. Terbium originates from the Earth's crust and undergoes a series of geological events that shape its distribution and concentration (Gupta and Krishnamurthy, 2016). Terbium is commonly found in alkaline igneous rocks, carbonatites, and hydrothermal veins (Chen et al., 2023). These environments provide the ideal conditions for the concentration of terbium-bearing minerals through processes such as magmatic differentiation, hydrothermal alteration, and weathering. Magmatic differentiation plays a essential role in concentrating terbium within specific rock types. During the cooling and crystallization of magma, certain elements, including terbium, become enriched in specific mineral phases, leading to the formation of terbium-rich minerals such as bastnasite, monazite, and xenotime (Gschneidner et al., 2016). Hydrothermal fluids circulating through the Earth's crust further contribute to the mobilization and redistribution of terbium, leading to the formation of hydrothermal mineral deposits enriched in terbium-bearing minerals. Surface weathering processes also play a significant role in reshaping terbium deposits. Through processes such as leaching, oxidation, and reprecipitation, primary terbium-bearing minerals undergo weathering, leading to the formation of secondary enrichment zones (Xu et al., 2020; McDonough and Sun, 2019). These secondary deposits contribute to the overall distribution and accessibility of terbium resources. Terbium is majorly found in minerals such as bastnasite, monazite, and xenotime, so in depth study of formation of terbium through these rocks are as below.

a. **Terbium in bastnasite:** Bastnasite is a rare earth carbonate mineral commonly found in carbonatite rocks. The formation of bastnasite is closely related to magmatic processes, specifically magmatic differentiation, and fractional crystallization (Table 2). During the cooling and crystallization of carbonatite magmas, minerals crystallize out sequentially based on their melting points. Bastnasite, being enriched in rare earth elements including terbium, crystallizes from the magma along with other minerals such as calcite and dolomite. This process of magmatic differentiation leads to the concentration of terbium within bastnasite-rich zones of carbonatite intrusions (Woolley, 2001).

The assimilation of terbium into bastnasite is governed by the mineral's crystal chemistry. Bastnasite has a general formula of $(Ce,La,Nd)(CO_3)F$, where Ce, La, and Nd are the primary rare earth elements, but other REEs, including terbium, can substitute into the structure. The substitution is facilitated by the similar ionic radii and charge of terbium compared to the other REEs present in bastnasite. Specifically, terbium (Tb^{3+}) can replace cerium (Ce^{3+}), lanthanum (La^{3+}), and neodymium (Nd^{3+}) in the crystal lattice due to their comparable sizes and trivalent state (Shannon, 1976). The geochemical environment plays a crucial role in the concentration and incorporation of terbium into bastnasite which includes factors such as the composition of the parent magma, the presence of fluorine, carbon dioxide, temperature, and pressure conditions influence the solubility and mobility of REEs. In environments where fluorine is abundant, the solubility of REEs increases, promoting the formation of fluorocarbonate minerals like bastnasite. The presence of carbon dioxide further aids in the stabilization of the bastnasite structure, allowing for higher incorporation rates of REEs, including terbium (Gaines et al., 1997).

b. **Terbium in Monazite:** Monazite is a phosphate mineral that typically forms in igneous and metamorphic rocks. Monazite formation involves both primary magmatic processes and secondary sedimentary processes (Table 2). The formation of monazite is associated with magmatic processes, particularly fractional crystallization. As igneous rocks undergo cooling and crystallization, monazite crystallizes from the magma alongside other minerals such as feldspars and quartz. Terbium can be incorporated into the crystal structure of monazite during its formation, leading to the enrichment of terbium within monazite-bearing rocks (Mitchell, 1996). Monazite is often associated with other REE-bearing minerals such as xenotime and zircon in these igneous settings (Mitchell, 1996). During secondary formation, monazite can also form through metamorphic processes, particularly in high-grade metamorphic rocks like schists and gneisses. In these environments, monazite crystallizes from the breakdown of other REE-bearing minerals during metamorphism. The mineral's stability under high temperature and pressure conditions makes it a common accessory mineral in metamorphic rocks (Franz, et al., 2015). Monazite is well-known for its occurrence in placer deposits, which are secondary deposits formed through sedimentary processes. These deposits form when monazite-bearing rocks are weathered and eroded, and the monazite grains are transported by water and deposited in riverbeds, beaches, and other sedimentary environments. Due to its high density and resistance to chemical and physical weathering, monazite accumulates in these placer deposits along with other heavy minerals like ilmenite, rutile, and zircon (Overstreet, 1967). In placer deposits, monazite can be concentrated through hydraulic sorting, where lighter minerals are washed away, leaving behind the heavier monazite grains (Table 2). These deposits are significant sources of monazite for REE extraction.

Table 2: Occurrences and distribution of Terbium deposit

Mineral Ore	Location	Geological Setting / Type of Deposit	Reference
Bastnasite	Andhra Pradesh, India	Carbonatite	Ramam and Viswanathan, 1977
Bastnasite	Gujarat, India	Alkaline Igneous Complex	Viladkar, 1986
Bastnasite	Bayan Obo, China	Carbonatite	Smith et al., 2000
Bastnasite	Dong Pao, Vietnam	Carbonatite	Notholt et al., 1990
Monazite	Odisha, India	Placer Deposit	Ghosal et al., 2020
Monazite	Kerala, India	Placer Deposit	Anitha et al., 2020
Monazite	Tamil Nadu, India	Placer Deposit	Singh, 2021
Monazite	West Bengal, India	Placer Deposit	Rao et al., 2018
Monazite	Maharashtra, India	Placer Deposit	Singh, 2021
Monazite	Mountain Pass, USA	Carbonatite	Mariano, 1989
Monazite	Araxá, Brazil	Carbonatite	Verplanck et al., 2016
Monazite	Tomtor, Russia	Carbonatite	Kravchenko et al., 2003
Monazite	Nechalacho, Canada	Alkaline Igneous Complex	Dostal, 2016

Xenotime	Mount Weld, Australia	Lateritic Weathering of Carbonatite	Hoatson et al., 2011
Xenotime	Kiruna, Sweden	Iron Oxide-Apatite (IOA) Deposits	Frietsch, 1978
Xenotime	Nolans Bore, Australia	Alkaline Igneous Complex	Huston et al., 2016

The incorporation of terbium into monazite is governed by the mineral's crystal chemistry. Monazite has a monoclinic crystal structure that can accommodate a range of REEs due to their similar ionic radii and trivalent charge. Terbium, being a trivalent cation, fits into the monazite lattice by substituting for other REEs like cerium, lanthanum, and neodymium. This substitution is facilitated by the ionic radius of terbium, which is like that of the other REEs typically found in monazite (Ni et al., 1995). The geochemical environment during the formation of monazite plays a crucial role in determining the concentration of terbium. Factors such as the composition of the parent magma, temperature, pressure, and the presence of fluids all influence the distribution of REEs within the crystallizing monazite. In environments with high concentrations of fluorine and phosphate, the solubility of REEs increases, leading to higher incorporation rates of elements like terbium into monazite (Heinrich, 1966).

c. **Terbium in Xenotime:** Xenotime is a rare earth phosphate mineral commonly found in pegmatites, granites, and other igneous rocks. Like bastnasite and monazite, xenotime formation is influenced by magmatic processes such as fractional crystallization. During the crystallization of igneous melts, xenotime crystallizes from the residual magma enriched in rare earth elements, including terbium (Table 2). The crystallization of xenotime occurs at relatively high temperatures and pressures, leading to its association with certain igneous environments (Franz, et al., 2015). Xenotime primarily forms in igneous rocks through magmatic differentiation and fractional crystallization. During the cooling of magma, minerals crystallize at different temperatures based on their chemical properties. As the magma evolves, it becomes enriched in rare earth elements, including terbium. Xenotime crystallizes from this evolved, silica-rich melt as it cools and solidifies. It is commonly found in granitic pegmatites, which are coarse-grained igneous rocks that crystallize from the last, most differentiated portions of a magma body. Pegmatites are particularly rich in rare earth elements, making them prime locations for xenotime formation (Elliott, 1991). Xenotime can also form in metamorphic rocks, particularly those that have undergone high-grade metamorphism. During metamorphism, existing minerals are altered by heat, pressure, and chemically active fluids, leading to the formation of new minerals. Xenotime can crystallize during these processes, often growing as an accessory mineral in metamorphic rocks such as schists and gneisses (Table 2).

The high-grade metamorphic conditions facilitate the incorporation of terbium and other rare earth elements into the xenotime crystal structure (Heinrich, 1966). Xenotime has a crystal structure that can accommodate a range of rare earth elements due to their similar ionic radii and charge. Terbium, like other rare earth elements, fits into the xenotime crystal lattice, substituting for yttrium and other rare earth elements. This substitution is supported by the similar size and charge of terbium ions compared to yttrium and other rare earth elements commonly found in xenotime (Ni et al., 1995).

APPLICATIONS OF TERBIUM

In recent years, terbium has become increasingly integral to numerous technological applications due to its unique properties (Graedel and Harper, 2018). Terbium finds extensive application in industries ranging from electronics to renewable energy, primarily owing to its magnetic, luminescent, and catalytic properties (Mat et al., 2017). Terbium is indispensable in the production of high-performance magnets used in electric vehicles, wind turbines, and electronic devices (Alonso et al., 2012). Its incorporation into phosphors enhances the efficiency and color rendering properties of fluorescent lamps and LEDs, contributing to energy efficiency initiatives. Terbium-based materials play a crucial role in catalysis, facilitating the synthesis of pharmaceuticals and fine chemicals. Its indispensability stems from its remarkable magnetic, luminescent, and catalytic properties, which render it irreplaceable in numerous industries (Alonso et al., 2012). As the demand for high-performance materials and energy-efficient technologies continues to soar, the significance of terbium in driving innovation and progress becomes increasingly pronounced.

Applications of Terbium and their Significance:

1. **Permanent Magnets:** Terbium is a key constituent in the production of high-performance magnets, particularly in neodymium-iron-boron (NdFeB) magnets used in electric vehicles, wind turbines, and various electronic devices (Graedel and Harper, 2018). Its incorporation enhances the magnetic properties, enabling the development of compact and efficient magnetic materials crucial for renewable energy generation and electrification initiatives. Without terbium, the performance and efficiency of these magnets would be significantly compromised, hindering technological progress in the renewable energy sector.
2. **Phosphors and Lighting:** The utilization of terbium compounds in phosphors revolutionizes lighting technology by enhancing the efficiency and color rendering properties of fluorescent lamps, compact fluorescent lamps (CFLs), and light-emitting diodes (LEDs) (Mat et al., 2017). Terbium-based phosphors enable the production of vibrant and energy-efficient lighting solutions vital for various applications, including residential, commercial, and industrial lighting. The absence of terbium would impede the development of energy-efficient lighting technologies, exacerbating energy consumption and environmental impacts associated with conventional lighting sources.
3. **Electronics and Displays:** Terbium-based materials play a pivotal role in electronic devices, including color television tubes, cathode-ray tubes (CRTs), and flat-panel displays, where they contribute to producing vibrant colors and high-definition images (Alonso et al., 2012). The exceptional luminescent properties of terbium are instrumental in enhancing display quality and ensuring an immersive viewing experience. Without terbium, the advancement of display technologies would be hindered, limiting the potential for innovation in entertainment, communication, and information dissemination.
4. **Catalysis:** Terbium compounds serve as catalysts in various organic synthesis reactions, facilitating the production of pharmaceuticals, fine chemicals, and polymers (Mat et al., 2017). The catalytic properties of terbium enable efficient and selective chemical transformations, enhancing the productivity and sustainability of chemical manufacturing processes. The absence of terbium-based catalysts would impede progress in drug discovery, materials science, and industrial chemistry, constraining the development of novel products and processes essential for societal advancement.

The unique properties of terbium, particularly its magnetic, luminescent, and catalytic properties, render it irreplaceable in numerous technological applications. Alternative materials lack the combination of characteristics offered by terbium, making it indispensable for achieving desired performance and functionality in various industries. The absence of terbium would not only impede technological progress but also hinder the transition towards a more sustainable and energy-efficient future. Thus, ensuring a stable supply of terbium and implementing responsible resource management practices are crucial for sustaining technological innovation and addressing global challenges.

CONCLUSION

The geological genesis of terbium is a multifaceted process driven by different mechanisms. Terbium exhibits variable oxidation states, primarily +3 and +4, with the +3 state being more stable and prevalent, while the +4 state, although less common, holds significant commercial value, especially in terbium(IV) oxide (Tb_4O_7). Terbium typically coexists with other rare earth elements (REEs) within geological settings such as alkaline igneous rocks, carbonatites, and hydrothermal veins. These environments enable the concentration of terbium through processes such as magmatic differentiation, hydrothermal alteration, and weathering. In carbonatite magmas, terbium is concentrated in bastnasite by substituting for other REEs during crystallization. Monazite, another major terbium-bearing mineral, forms through both primary magmatic processes and secondary sedimentary processes, accumulating in igneous, metamorphic, and placer deposits. Xenotime, commonly found in pegmatites and granites, incorporates terbium during the high-temperature crystallization of evolved magmas and within high-grade metamorphic rocks. The crystal chemistry of these minerals facilitates the substitution of terbium for other REEs, owing to the similarities in their ionic radii and charges, influenced by the geochemical environment during mineral formation. Terbium's unique magnetic, luminescent, and catalytic properties are critical for numerous advanced technological applications, including high-performance magnets essential for renewable energy technologies, energy-efficient lighting solutions, and vibrant electronic displays. The absence of terbium would impede progress in electric vehicles, wind turbines, and electronic devices, limiting advancements towards a sustainable and energy-efficient future. Therefore, ensuring a stable supply of terbium, alongside responsible resource management practices, is crucial for sustaining technological innovation and effectively addressing global challenges.

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REFERENCES

1. Alomari, A.D., Alezi, D., and Abdel Salam, M. (2023). Synthesis and characterization of terbium-based metal organic framework for environmental remediation application. Catalysts, 13(2), 241. https://doi.org/10.3390/catal13020241.
2. Alonso, E., Sherman, A. M., Wallington, T. J., Everson, M. P., Field, F. R., Roth, R., et al. (2012). Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ. Sci. Technol. 46, 3406–3414. doi:10.1021/es203518d
3. Anitha, J. K., Joseph, S., Rejith, R. G., and Sundararajan, M. (2020). Monazite chemistry and its distribution along the coast of Neendakara–Kayamkulam belt, Kerala, India. SN Applied Sciences, 2(5). doi:10.1007/s42452-020-2594-6
4. Chakhmouradian, A.R., and Wall, F. (2012). Rare earth elements: Minerals, mines, magnets (and more). Elements, 8(5), 333-340.
5. Chen, W., Zhang, Z., Long, F., Chen, Z., and Chi, R. (2023). Rare earth occurrence states of weathered crust elution-deposited rare earth ores in Southern Yunnan. Minerals, 13(4), 554.
6. Dostal, J. (2016). Rare Metal Deposits Associated with Alkaline/Peralkaline Igneous Rocks. Society of Economic Geologists, 6-34.
7. Edelmann, F. T. and Poremba, P. (1997). Herrmann, W. A. (ed.). Synthetic Methods of Organometallic and Inorganic Chemistry. American Chemical Society, 6, 182p.
8. Elliott, H. (1991). The Rare Earth Elements: Chemistry, Origin, and Ore Deposits. Springer.
9. Franz, G., Morteani, G., and Rhede, D. (2015). Xenotime-(Y) formation from zircon dissolution–precipitation and HREE fractionation: an example from a metamorphosed phosphatic sandstone, Espinhaço fold belt (Brazil). Contributions to Mineralogy and Petrology, 170, 37. https://doi.org/10.1007/s00410-015-1191-y.
10. Frietsch, R. (1978) On the Magmatic Origin of Iron Ores of the Kiruna Type. Economic Geology, 73, 478-485. http://dx.doi.org/10.2113/gsecongeo.73.4.478
11. Gaines, R.V., Skinner, H.C., Foord, E.E., Mason, B., and Rosenzweig, A. (1997). Dana's New Mineralogy: The System of Mineralogy of James Dwight Dana and Edward Salisbury Dana. Wiley, 46p.
12. Ghosal, S., Agrahari, S., Banerjee, S., Chakrabarti, R., and Sengupta, D. (2020). Geochemistry of the heavy mineral sands from the Garampeta to the Markandi beach, southern coast of Odisha, India:

Implications of high contents of REE and radioelements attributed to placer monazite. Journal of Earth System Science, 129(1). https://doi.org/10.1007/s12040-020-01419-8.

13. Graedel, T. E., and Harper, E. M. (2018). Rare Earths and their Uses. In Critical Metals Handbook, Wiley.

14. Gschneidner Jr, K. A., Bünzli, J. C. G., and Pecharsky, V. K. (Eds.). (2016). Handbook on the Physics and Chemistry of Rare Earths, Elsevier, 50.

15. Gupta, C. K., and Krishnamurthy, N. (2016). Extractive metallurgy of rare earths. CRC Press.

16. Hartmut Bergmann and Leopold Gmelin (1986). Gmelin Handbook of Inorganic Chemistry, System Number 39. Springer-Verlag.

17. Heinrich, E.W. (1966). The Geology of Carbonatites. Rand McNally.

18. Hoatson, D. M., Jaireth, S., and Miezitis, Y. (2011). The major rare-earth-element deposits of Australia: geological setting, exploration, and resources. Geoscience Australia, 204.

19. Huston, D.L., Wygralak, A.S., and Mernagh, T.P. (2016). Rare earth element minerals in the Nolans Bore deposit, Northern Territory, Australia. *Mineralium Deposita*, 51(6), 797-822.

20. Imashuku, S. (2024). Distinguishing xenotime and zircon in ores and estimating the xenotime content for on-site analysis. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 315, 124216. https://doi.org/10.1016/j.saa.2024.124216.

21. Kravchenko, S.M., Czamanske, G., and Fedorenko, V.A. (2003). Geochemistry of carbonatites of the Tomtor massif. Geochemistry International, 41, 545-558.

22. Mariano, A.N. (1989). Economic geology of rare earth elements. *Reviews in Mineralogy and Geochemistry*, 21(1), 309-337.

23. Mariano, A.N., and Mariano, A. (2012). Rare earth mining and exploration in North America. Elements, 8(5), 369-376.

24. Mat Suli, L., Ibrahim, W., Abdul Aziz, B., Deraman, M.R., and Ismail, N. (2017). A review of rare earth mineral processing technology. Chemical Engineering Research Bulletin, 19- 20. https://doi.org/10.3329/cerb.v19i0.33773.

25. McDonough, W., and Sun, S.-s. (1995). The composition of the Earth. Chemical Geology, 120, 223-253.

26. Mitchell, R.H. (1996). Petrology of Lamproites. Springer Science and Business Media.

27. Ni, Y., Hughes, J.M., and Mariano, A.N. (1995). Crystal chemistry of the monazite and xenotime structures. American Mineralogist, 80(1-2), 21-26.

28. Notholt, A.J.G., Sheldon, R.P., and Davidson, D.F. (1990). *Phosphate Deposits of the World*. Cambridge University Press.

29. Overstreet, W.C. (1967). The Geologic Occurrence of Monazite. U.S. Geological Survey Professional Paper, 530.

30. Ramam, P.K., and Viswanathan, T.V. (1977). Carbonatite complex near Borra, Visakhapatnam District, Andhra Pradesh. Indian Minerals, 18(11), 605-610.

31. Rao, M.J., Raju, U.P.N., Rao, G.R., and Mounika, K.S.S. (2018). Beach placer deposits of India, their distribution, mineralogy, and sustainable mining with reference to placer ilmenite. International Journal of Science and Research (IJSR), 7(5). https://www.ijsr.net.

32. Shannon, R.D. (1976). Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. Acta Crystallographica Section A: Crystal Physics, Diffraction, Theoretical and General Crystallography, 32(5), 751-767.

33. Singh, Y. (2021). Rare Earth Element Geochemistry of Monazites from Beach Sand Deposits of Indian Coasts: Implications for Clean Energy. 22, 209-220.

34. Smith, M.P., Henderson, P., and Campbell, L.S. (2000). Fractionation of the REE during hydrothermal processes: Constraints from the Bayan Obo Fe-REE-Nb deposit, Inner Mongolia, China. Geochimica et Cosmochimica Acta, 64(19), 3141-3160.

35. Verplanck, P.L., and Hitzman, M.W. (2016). Rare earth and critical elements in ore deposits. Reviews in Economic Geology, 18. Society of Economic Geologists.

36. Viladkar, S.G. (1986). Rare earth element abundances in carbonatites, alkaline rocks, and fenites of the Amba Dongar complex, Gujarat, India. Journal of the Geological Society of India, 1, 37-48.

37. Wall, F., and Mariano, A.N. (1996). Rare earth minerals in carbonatites: A discussion centered on the Kangankunde Carbonatite, Malawi. In Jones, A.P., Wall, F., and Williams, C.T. (Eds.), Rare Earth Minerals: Chemistry, Origin and Ore Deposits, 193-225

38. Woolley, A.R. (2001). Carbonatites: Nomenclature, Average Chemical Composition, and Element Distribution. In: Rare Earth Minerals: Chemistry, Origin and Ore Deposits. CRC Press.

39. Xu, M.J., Si, J.Y., Li, G.H., Liu, Y.J., Cai, G.M., and Zhang, J. (2020). Structure, tunable luminescence and thermal stability in Tb^{3+} and Eu^{3+} co-doped novel $KBaIn_2(PO_4)_3$ phosphors. Journal of Luminescence, 221, 117115.

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