Alkaline–Carbonatite Complexes of India: A Review of Geological Evolution and Critical Mineral Resources

S. Ranjithkumar[1], S. Anbazhagan[1,2,*]

[1]Centre for Geoinformatics and Planetary studies, Department of Geology, Periyar University, Salem-636011, India.

[2]School of Natural Science and Engineering, National Institute of Advanced Studies, IISc Campus, Bengaluru- 560012, India.

***Corresponding Author**

DOI: https://doi.org/10.51244/IJRSI.2026.1307000075

Received: 12 July 2026; Accepted: 17 July 2026; Published: 28 July 2026

ABSTRACT

The alkaline–carbonatite complexes of India constitute some of the most significant repositories of rare earth elements (REEs), niobium (Nb), phosphorus (P), barium (Ba), strontium (Sr), uranium (U), thorium (Th), and other critical minerals that are indispensable for modern technologies and the global transition towards clean energy. These complexes are predominantly distributed within the Precambrian shield of Peninsular India and are spatially associated with deep-seated crustal fractures, continental rift systems, and major shear zones, reflecting prolonged mantle-derived alkaline magmatism and tectonic reactivation. Extensive geological, geochemical, and geochronological investigations over the past five decades have considerably improved the understanding of the origin, evolution, and economic significance of Indian alkaline–carbonatite complexes. This review synthesizes the previous work on geological setting, geochemistry, isotope characteristics, petrogenesis, tectonic evolution, and critical mineral resources of the alkaline–carbonatite complexes of India. The research work consistently demonstrate that Indian carbonatites originated from mantle-derived carbonatitic magmas that evolved through varying degrees of partial melting, fractional crystallization, carbonate–silicate liquid immiscibility, metasomatism, hydrothermal alteration, fenitization, and supergene enrichment. The principal alkaline–carbonatite provinces of India include the Amba Dongar, Kamthai, Sung Valley, Samchampi, Newania, Mundwara, Sarnu–Dandali, Sevathur, Samalpatti, Hogenakkal, Pakkanadu, Pikkili and Kambamettu complexes. Among these, the alkaline–carbonatite complexes of Tamil Nadu represent one of the most extensively investigated provinces, providing important constraints on mantle evolution, crust–mantle interaction, alkaline magmatism, and critical mineral enrichment. Recent advances in mineral chemistry and exploration techniques have further highlighted the strategic importance of Indian carbonatites as potential domestic sources of rare earth elements and other critical minerals. This article summarizes the present understanding of Indian alkaline–carbonatite complexes and identifies future directions for geological research and mineral exploration.

Keywords: Alkaline; Carbonatites; Petrogenesis; Geochemistry; REE.

INTRODUCTION

Alkaline–carbonatite complexes represent a distinctive group of mantle-derived igneous rocks characterized by their unusual mineralogical composition, enrichment in incompatible trace elements, and close spatial association with continental rifts, deep-seated faults, and lithospheric-scale tectonic structures. Carbonatites are igneous rocks containing more than 50% modal carbonate minerals and commonly occur together with alkaline silicate rocks such as syenites, ijolites, nepheline syenites, pyroxenites, and fenites. Owing to their enrichment in rare earth elements (REEs), niobium (Nb), phosphorus (P), fluorine (F), barium (Ba), strontium (Sr), uranium (U), thorium (Th), and other incompatible elements, carbonatites constitute one of the world's most important sources of critical mineral resources.

India possesses numerous alkaline–carbonatite complexes distributed throughout the Precambrian shield, particularly within the Southern Granulite Terrain, Eastern Ghats Mobile Belt, Rajasthan, Gujarat, Meghalaya, and associated tectonic provinces. These complexes have attracted considerable scientific attention because they provide valuable information like mantle metasomatism, alkaline magmatism, crust–mantle interaction, and continental tectonic evolution. Simultaneously, they have emerged as strategically important exploration targets owing to their substantial concentrations of REE and associated critical minerals.

Petrological and geochemical studies indicate that Indian carbonatites evolved through multiple magmatic and post-magmatic processes including low-degree partial melting of metasomatized mantle, fractional crystallization, carbonate–silicate liquid immiscibility, hydrothermal alteration, fenitization, and supergene enrichment (Natarajan et al., 1994; Schleicher et al., 1998; Pandit et al., 2002; Upadhyay et al., 2021; Mohanty et al., 2026).

The increasing global demand for REE, niobium, and other strategic metals for renewable energy technologies, electric vehicles, defence applications, and advanced electronics has significantly enhanced the exploration importance of alkaline–carbonatite complexes. Recent investigations combining mineral chemistry, isotope geochemistry, fluid inclusion studies, geochronology, and remote sensing have substantially improved the understanding of carbonatite evolution and REE mineralization across the country (Balaram, 2019; Krishnamurthy, 2019; Singh, 2020; Randive & Meshram, 2020; Aranha et al., 2022). The objective of this review is to comprehensively synthesize previous work on the geological distribution, petrology, geochemistry, isotope characteristics, petrogenesis, tectonic evolution, and critical mineral resources of Indian alkaline–carbonatite complexes.

GEOLOGICAL SETTINGS AND DISTRIBUTION

The alkaline–carbonatite complexes of India are predominantly distributed within the Precambrian shield and are closely associated with major tectonic lineaments, shear zones, deep-seated crustal fractures, continental rift systems, and mobile belts, suggesting that lithospheric extension and deep mantle-derived magmatism played a major role in their emplacement. Their spatial relationship with long-lived lithospheric structures indicates that repeated episodes of mantle-derived alkaline magmatism were controlled by tectonic reactivation and crustal extension. Geological investigations have shown that these complexes typically comprises of carbonatites, pyroxenites, syenites, ijolites, dunites, gabbros, and fenites, reflecting complex magmatic differentiation and extensive metasomatic alteration (Udas & Krishnamurthy, 1969; Krishnamurthy et al., 2000; Krishnamurthy, 2019; Randive & Meshram, 2020). These complexes occur mainly within the Southern Granulite Terrain (SGT), Eastern Ghats Mobile Belt (EGMB), Rajasthan Craton, Gujarat Alkaline Province, Meghalaya Plateau, and the Chhotanagpur Gneissic Complex, where they are emplaced into Archean to Proterozoic crystalline basement rocks (Krishnamurthy et al., 2000; Krishnamurthy, 2019; Randive & Meshram, 2020; Paul et al., 2020).

Indian carbonatites commonly occur in association with alkaline silicate rocks such as pyroxenites, ijolite, syenite, dunite, gabbro, and fenite, forming composite intrusive complexes that represent multiple phases of alkaline magmatism. Field relationships, petrographic observations, and geochemical data indicate that these complexes were emplaced through successive intrusive events involving both silicate and carbonate magmas. Fenitization of the country rocks is a characteristic feature of most Indian complexes, indicating extensive alkali metasomatism during magma emplacement (Udas & Krishnamurthy, 1969; Subramaniam et al., 1978; Viladkar & Subramanian, 1995; Krishnamurthy, 2019).

Western India

Several alkaline–carbonatite provinces have been recognized across India. In western India, the Gujarat alkaline province contains the well-known Amba Dongar carbonatite complex together with the Chhota Udaipur alkaline province. These complexes consist predominantly of calcite, dolomite, and ankerite rich carbonatites associated with alkaline silicate rocks and host significant concentrations of niobium and light rare earth elements. Detailed mineralogical and geochemical studies have demonstrated extensive hydrothermal alteration and supergene modification that enhanced REE and Nb mineralization within pyrochlore, bastnäsite, monazite, apatite, and

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

related accessory minerals (Viladkar, 2019; Magna et al., 2020; Viladkar & Sorokhtina, 2021; Mohanty et al., 2026).

Western Rajasthan represents another important alkaline province containing the Kamthai, Sarnu–Dandali, Mundwara, and Mer carbonatite complexes. These intrusions are associated with the Malani igneous suite and tertiary alkaline magmatism and have emerged as India's most prospective REE-bearing carbonatite systems. Geological investigations have documented abundant bastnäsite, synchysite, ancylite, parisite, carbocernaite, pyrochlore, and apatite together with significant enrichment of La, Ce, Nd, Nb, Sr, and Ba, indicating considerable economic potential for critical mineral development (Bhushan & Kumar, 2013; Singh, 2020; Upadhyay et al., 2021; Aranha et al., 2022). The Newania carbonatite complex of Rajasthan represents one of the oldest recognized carbonatite occurrences in India and has provided valuable information regarding Precambrian carbonatite magmatism. Pb–Pb isotope studies together with whole-rock geochemistry have demonstrated its mantle affinity and highlighted similarities with the Neoproterozoic carbonatite complexes of southern India (Schleicher et al., 1997).

Southern Granulitic Terrain, India

The state of Tamil Nadu hosts one of the most important alkaline–carbonatite provinces in India and has served as a natural laboratory for understanding the origin, evolution, and economic significance of carbonatitic magmatism. The alkaline complexes are primarily distributed within the Southern Granulite Terrain (SGT), where they intrude Archean high-grade metamorphic rocks including charnockites, hornblende–biotite gneisses, granulites, amphibolites, and migmatitic gneisses. Their emplacement is closely associated with major crustal-scale structures such as the Dharmapuri Rift Zone, the Koratti–Attur fault system, the Moyar–Bhavani shear zone, and other northeast–southwest-trending tectonic lineaments. These structural corridors acted as conduits for repeated mantle-derived alkaline magmatism during the Neoproterozoic, resulting in the emplacement of several carbonatite and alkaline rock complexes across northern and western Tamil Nadu (Subramaniam et al., 1978; Kumar et al., 1998; Miyazaki et al., 2000; Kumar et al., 2001; Krishnamurthy, 2019; Ray & Parthasarathy, 2019).

The principal alkaline–carbonatite complexes of Tamil Nadu include Sevathur, Samalpatti, Hogenakkal, Pakkanadu, Pikkili, Jogipatti, Kambamettu, Yelagiri, Sivamalai, Sundamalai, Chalk Hills, Rasimalai, Kamaneri, and several smaller alkaline intrusions. Although each complex exhibits distinctive geological characteristics, they collectively represent products of mantle-derived alkaline magmatism emplaced during multiple tectono-magmatic episodes. Their close spatial association with deep-seated faults and shear zones strongly indicates that lithospheric extension and tectonic reactivation played fundamental roles in controlling magma ascent and emplacement (Krishnamurthy et al., 2000; Kumar et al., 2001; Ray & Parthasarathy, 2019).

The Sevathur carbonatite complex, located in the northern part of Tamil Nadu, is one of the most extensively investigated carbonatite occurrences in India. The complex consists predominantly of calcitic and dolomitic carbonatites associated with pyroxenites, syenites, ijolites, fenites, and ultramafic rocks. Geological mapping demonstrates that carbonatite intrusions occur as plugs, veins, dykes, and irregular bodies emplaced within Archean granulitic basement rocks. Fenitization is well developed around the intrusive contacts, indicating intense alkali metasomatism associated with carbonatitic fluids (Udas & Krishnamurthy, 1969; Natarajan et al., 1994; Krishnamurthy et al., 2000).

The Samalpatti carbonatite complex represents another important alkaline intrusion within the Dharmapuri alkaline province. The complex is composed mainly of calcitic and dolomitic carbonatites associated with pyroxenites, syenites, fenites, and ultramafic rocks. Petrographic observations reveal abundant calcite together with apatite, amphibole, pyroxene, barite, magnetite, pyrochlore, and accessory REE-bearing minerals. Stable isotope investigations indicate that primary mantle-derived carbonatite magmas subsequently experienced hydrothermal alteration and isotopic exchange with circulating fluids, resulting in oxygen isotope enrichment while largely preserving their original carbon isotope signatures. These observations suggest that Samalpatti records both primary magmatic processes and extensive post-magmatic hydrothermal evolution (Srivastava & Taylor, 1996; Schleicher et al., 1998).

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

The Hogenakkal carbonatite complex is among the oldest recognized carbonatite occurrences in India and provides important evidence for Paleoproterozoic alkaline magmatism within the Southern Granulite Terrain. The complex comprises carbonatites associated with pyroxenites, syenites, and fenitized country rocks. Geochronological investigations suggest that the Hogenakkal intrusion predates many other alkaline complexes of southern India, making it particularly significant for understanding the long-term evolution of the Indian lithosphere (Natarajan et al., 1994; Krishnamurthy, 2019). The whole-rock geochemistry reveals that enrichment in calcium, phosphorus, barium, strontium, niobium, and light rare earth elements. The petrographic studies demonstrate extensive carbonate recrystallization and hydrothermal replacement. These observations indicate that the Hogenakkal carbonatites evolved through repeated magmatic differentiation followed by fluid-mediated alteration and mineral redistribution.

The Pakkanadu alkaline–carbonatite complex has recently become one of the most important rare earth element prospects in southern India. Detailed petrographic, mineralogical, and geochemical investigations have identified abundant monazite-(Ce), allanite-(Ce), chevkinite-(Ce), fluorapatite, pyrochlore, strontianite, barite, zircon, and magnetite within calcitic carbonatites. Whole-rock geochemical analyses demonstrate exceptional enrichment in light rare earth elements, particularly La, Ce, and Nd, together with high concentrations of Ba, Sr, Nb, and phosphorus (Mahapatro et al., 2023). Mineral chemistry indicates that carbo-hydrothermal fluids played a crucial role in redistributing and concentrating REEs after primary magmatic crystallization. Replacement textures involving apatite, pyrochlore, and carbonate minerals demonstrate that hydrothermal processes significantly upgraded the rare earth element content of the complex, thereby enhancing its economic potential.

The Pikkili carbonatite complex forms part of the northern Tamil Nadu alkaline province and is closely associated with pyroxenites, syenites, and fenitized country rocks. Although comparatively less studied than Sevathur and Samalpatti, available geological investigations indicate similar petrological evolution involving mantle-derived carbonatitic magma followed by alteration (Krishnamurthy et al., 2000; Krishnamurthy, 2019).

North Eastern India

In north-eastern India, the Sung Valley and Samchampi carbonatite complexes constitute important alkaline provinces related to continental extension and mantle-derived magmatism. These complexes contain abundant apatite, pyrochlore, monazite, bastnäsite, fluorite, and associated REE-bearing minerals, making them attractive targets for exploration of strategic mineral resources (Krishnamurthy et al., 2000; Balaram, 2019; Krishnamurthy, 2019).

PETROGRAPHY AND MINERALOGY

The alkaline–carbonatite complexes of India display remarkable lithological and mineralogical diversity, reflecting complex magmatic differentiation, mantle metasomatism, hydrothermal alteration, and prolonged post-magmatic evolution. Carbonatites commonly occur as plugs, ring complexes, veins, dykes, lenses, and irregular intrusive bodies closely associated with alkaline silicate rocks such as pyroxenites, syenites, ijolites, nepheline syenites, dunite, gabbro, and fenites. Field relationships indicate that carbonatite magmatism generally represents the final intrusive phase of alkaline magmatic evolution, although multiple intrusive episodes have been recognized in several complexes (Udas & Krishnamurthy, 1970; Subramaniam et al., 1978; Viladkar & Subramanian, 1995; Krishnamurthy, 2019).

Petrographic investigations reveal that Indian carbonatites exhibit coarse-grained granular, inequigranular, porphyritic, brecciated, and vein-like textures. Carbonate minerals commonly occur as euhedral to subhedral crystals with interstitial apatite, magnetite, pyrochlore, barite, amphibole, phlogopite, aegirine, and feldspar. Secondary replacement textures, recrystallization, carbonate veining, and oxidation features are widespread, indicating extensive post-magmatic alteration. Fenitization of the surrounding country rocks is a characteristic feature of nearly all major Indian carbonatite complexes and is manifested by alkali metasomatism, development of alkali amphiboles and pyroxenes, feldspathization, carbonatization, and enrichment of sodium and potassium (Subramaniam et al., 1978; Ramasamy, 2012; Krishnamurthy, 2019).

Rare earth element mineralization in Indian carbonatites is hosted by a variety of primary and secondary minerals including bastnäsite, monazite, allanite, synchysite, parisite, ancylite, carbocernaite, chevkinite, cerianite, fluorapatite, and britholite-like phases. These minerals occur either as disseminated crystals within carbonatites or as hydrothermal replacements associated with barite, fluorite, quartz, hematite, and secondary carbonate minerals. Petrographic evidence indicates that many REE minerals formed during late magmatic to hydrothermal stages through fluid-assisted remobilization and precipitation (Bhushan & Kumar, 2013; Upadhyay et al., 2021; Mahapatro et al., 2023; Mohanty et al., 2026).

Indian carbonatites are conventionally classified into calcio-carbonatites (sövites), magnesio-carbonatites (beforsites), and ferro-carbonatites based on their dominant carbonate mineralogy. Calcitic carbonatites are the most widespread and are composed predominantly of coarse-grained calcite with subordinate apatite, magnetite, pyrochlore, barite, amphibole, biotite, and accessory REE-bearing minerals. Magnesio-carbonatites are characterized by abundant dolomite and ankerite, whereas ferro-carbonatites contain Fe-rich carbonate minerals associated with magnetite and hematite. These lithological variations record progressive differentiation of carbonatitic magma together with hydrothermal and metasomatic modifications during cooling (Viladkar & Subramanian, 1995; Krishnamurthy, 2019; Randive & Meshram, 2020).

Calcite and dolomite constitute the dominant carbonate minerals throughout most Indian carbonatites. Their relative abundance varies among individual complexes and frequently records different stages of magmatic evolution. Ankerite commonly develops during later hydrothermal stages and is associated with iron enrichment, secondary carbonate replacement, and alteration of primary calcitic assemblages. Mineralogical studies have demonstrated that many carbonatites preserve multiple generations of carbonate minerals produced during successive magmatic and hydrothermal events (Viladkar & Subramanian, 1995; Schleicher et al., 1997; Mohanty et al., 2026).

Among the accessory minerals, apatite represents one of the most abundant and economically important phases. It commonly occurs as euhedral to subhedral crystals disseminated throughout carbonatites or concentrated within apatite-rich zones. Besides serving as the principal host of phosphorus, apatite accommodates substantial concentrations of REE and strontium through coupled substitutions. Recent mineral chemical investigations have shown that apatite also records progressive hydrothermal modification and REE enrichment, making it an important indicator of magmatic evolution and ore-forming processes (Schleicher, 2019; Upadhyay et al., 2021; Mohanty et al., 2026).

Pyrochlore is the principal niobium-bearing mineral in most Indian carbonatites and exhibits considerable compositional variation resulting from magmatic crystallization followed by hydrothermal and supergene alteration. Primary pyrochlore is generally rich in Ca, Na, Nb, and F, whereas altered varieties show depletion of alkalis together with enrichment in Pb, U, Th, Ti, Zr, Ba, and rare earth elements. Complex zoning, replacement textures, and metamictization indicate prolonged interaction between carbonatitic minerals and late-stage fluids, particularly within the Amba Dongar, Kamthai, Sevathur, and Saidiwasan carbonatite complexes (Magna et al., 2020; Viladkar & Sorokhtina, 2021; Dey et al., 2021; Mohanty et al., 2026).

Magnetite occurs as both primary magmatic crystals and secondary hydrothermal products. Petrographic and mineral chemical investigations from the Sevathur complex distinguish euhedral titanomagnetite phenocrysts produced during magmatic crystallization from fine-grained secondary magnetite generated through oxidation and decomposition of iron-rich carbonate minerals. Similar relationships have been documented in several other Indian complexes, demonstrating that iron oxide mineralization evolved throughout multiple stages of carbonatite emplacement and cooling (Ramasamy et al., 2001; Upadhyay et al., 2021).

Several Indian carbonatite complexes contain rare carbonate minerals that provide valuable insights into crystallization conditions. Benstonite, an uncommon barium-rich carbonate mineral, has been reported from the Jogipatti and Samalpatti carbonatites of Tamil Nadu and represents one of the most distinctive mineralogical characteristics of these complexes. Its occurrence together with calcite, dolomite, aegirine, orthoclase, and monazite suggests crystallization from highly evolved carbonatitic magma enriched in barium and strontium rather than formation by low-temperature hydrothermal processes (Semenov et al., 1971; Vladykin et al., 2008).

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

The alkaline silicate rocks associated with carbonatites also exhibit considerable mineralogical diversity. Pyroxenites are dominated by diopside, aegirine, aegirine-augite, and titanaugite, whereas syenites consist mainly of alkali feldspar, perthite, amphibole, biotite, and subordinate quartz. Dunite and ultramafic rocks contain olivine together with clinopyroxene and amphibole, recording interaction between carbonatitic melts and mantle peridotite. Recent investigations have documented unusual low-Ni olivine xenocrysts within the Sevathur carbonatites, providing direct evidence for mantle-derived xenocryst incorporation and melt–mantle interaction during carbonatite evolution (Meshram & Randive, 2024).

Overall, the petrological and mineralogical characteristics of Indian alkaline–carbonatite complexes demonstrate a prolonged history of mantle-derived magmatism followed by fractional crystallization, carbonate–silicate liquid immiscibility, alkali metasomatism, hydrothermal alteration, and supergene weathering. These processes collectively produced the remarkable mineralogical diversity observed in Indian carbonatites and were primarily responsible for concentrating economically important rare earth elements, niobium, phosphorus, barium, strontium, uranium, thorium, and associated critical minerals. Consequently, the mineral assemblages preserved within these complexes provide valuable information on magma evolution while simultaneously representing important exploration targets for strategic mineral resources.

GEOCHEMISTRY AND ISOTOPIC STUDIES

The geochemical characteristics of Indian alkaline–carbonatite complexes provide important constraints on their mantle origin, magmatic evolution, tectonic setting, and ore-forming processes. Comprehensive investigations involving whole-rock major and trace element geochemistry, rare earth element (REE) distribution patterns, radiogenic isotopes, stable isotopes, and geochronology consistently indicate that carbonatites originated from mantle-derived magmas that subsequent alteration processes. Although individual complexes display variations in mineralogy and chemistry, they exhibit several common geochemical signatures that distinguish them from other carbonate-rich rocks (Udas & Krishnamurthy, 1969; Natarajan et al., 1994; Ackerman., 2017; Krishnamurthy, 2019; Randive & Meshram, 2020).

Whole-rock geochemical analyses show that Indian carbonatites are enriched in CaO, MgO, Fe_2O_3, CO_2, P_2O_5, Sr, Ba, Nb, Th, U, Zr, and light rare earth elements (LREEs), whereas SiO_2, Al_2O_3, Na_2O, and K_2O generally occur in comparatively lower concentrations than in associated alkaline silicate rocks. Variations in major oxide compositions largely reflect differences in the proportions of calcite, dolomite, ankerite, apatite, magnetite, and accessory silicate minerals, together with varying degrees of magmatic differentiation and hydrothermal modification (Subramaniam et al., 1978; Viladkar & Subramanian, 1995; Subramani, 2017).

Trace element distributions are characterized by exceptionally high concentrations of incompatible elements including Nb, Ba, Sr, La, Ce, Nd, Th, U, and P. Such enrichment is attributed to the highly incompatible nature of these elements during mantle melting and their progressive concentration during magmatic differentiation. Pyrochlore serves as the principal host for niobium, whereas apatite, monazite, bastnäsite, allanite, and associated REE-bearing minerals accommodate substantial quantities of rare earth elements. Barium and strontium occur both within primary carbonate minerals and in accessory phases such as barite, benstonite, and strontianite, reflecting both magmatic and hydrothermal enrichment processes (Krishnamurthy et al., 2000; Balaram, 2019; Singh, 2020).

Radiogenic isotope studies have significantly improved understanding of the mantle source regions responsible for Indian alkaline–carbonatite magmatism. Strontium and neodymium isotope investigations consistently indicate derivation from enriched subcontinental lithospheric mantle, although several studies recognize contributions from both enriched and depleted mantle reservoirs depending on the age and location of individual complexes. Initial ^87Sr/^86Sr ratios together with negative εNd values generally support magma generation from long-lived metasomatized mantle rather than significant crustal contamination. Nevertheless, minor isotopic variations among complexes indicate local heterogeneity within the mantle source and varying degrees of interaction with crustal rocks during magma ascent (Natarajan et al., 1994; Schleicher et al., 1998; Kumar et al., 1998; Miyazaki et al., 2000; Krishnamurthy, 2019).

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

Stable carbon and oxygen isotope compositions further confirm the primary mantle origin of Indian carbonatitic magmas. Several complexes, including Koratti–Sevathur and Mundwara, possess $\delta^{13}C$ and $\delta^{18}O$ values that fall within the field of primary igneous carbonatites, indicating minimal post-magmatic modification. In contrast, complexes such as Samalpatti, Amba Dongar, and Kala Doongar exhibit enrichment in oxygen isotopes resulting from hydrothermal alteration, meteoric water interaction, Rayleigh fractionation, and low-temperature isotopic exchange after emplacement. These variations demonstrate that although mantle signatures are generally preserved, post-magmatic processes significantly modified the isotopic composition of many Indian carbonatites (Srivastava & Taylor, 1996; Schleicher et al., 1998; Pandit et al., 2002; Rapprich et al., 2017).

Lead isotope investigations provide additional evidence for mantle-derived magmatism and have been particularly useful in constraining the ages and evolution of Indian carbonatite complexes. Whole-rock Pb–Pb isotope analyses from the Sevathur and Newania complexes yielded Neoproterozoic emplacement ages of approximately 800 Ma and demonstrated multistage magmatic evolution involving successive intrusions of dolomitic, calcitic, and ankeritic carbonatites. Elevated concentrations of radiogenic lead together with uranium-rich pyrochlore indicate prolonged magmatic differentiation followed by hydrothermal remobilization of incompatible elements (Schleicher et al., 1997; Schleicher et al., 1998).

The age of alkaline–carbonatite magmatism in India spans a considerable geological interval from the Paleoproterozoic to the Cretaceous, reflecting multiple tectono-magmatic episodes. Geochronological investigations suggest that the older plutonic carbonatites are largely confined to the Precambrian shield, whereas younger subvolcanic carbonatite complexes are associated with Cretaceous extensional tectonics. These magmatic events have been linked to continental rifting, mantle metasomatism, lithospheric extension, and Pan-African tectono-thermal reactivation, indicating prolonged evolution of the Indian lithosphere (Schleicher et al., 1997; Kumar et al., 1998; Miyazaki et al., 2000; Paul et al., 2020). Hogenakkal represents one of the oldest known carbonatite complexes in India, with emplacement during the Paleoproterozoic, whereas the Sevathur and Samalpatti complexes are predominantly Neoproterozoic in age. Younger alkaline provinces such as Amba Dongar and Kamthai are associated with Cretaceous tectono-magmatic activity related to continental extension. This prolonged history demonstrates repeated reactivation of lithospheric structures and multiple episodes of mantle-derived alkaline magmatism throughout the geological evolution of the Indian shield (Natarajan et al., 1994; Kumar et al., 1998; Miyazaki et al., 2000; Paul et al., 2020).

Hydrothermal alteration exerts a major influence on the geochemical evolution of Indian carbonatites. Petrographic observations, mineral chemistry, isotope data, and fluid–rock interaction studies indicate that late-stage hydrothermal fluids redistributed REEs, Nb, Ba, Sr, U, Th, and other incompatible elements, resulting in extensive replacement of primary minerals and precipitation of secondary REE-bearing phases. Processes such as hematitization, silicification, baritization, carbonatization, and oxidation of magnetite played important roles in upgrading the concentrations of economically valuable minerals, particularly in the Kamthai, Amba Dongar, Pakkanadu, Sevathur, and Saidiwasan complexes (Magna et al., 2020; Upadhyay et al., 2021; Mahapatro et al., 2023; Mohanty et al., 2026).

Overall, geochemical, isotopic, and geochronological evidence demonstrates that Indian alkaline–carbonatite complexes originated from low-degree partial melting of metasomatized subcontinental lithospheric mantle and subsequently evolved through various processes. These processes collectively controlled the enrichment and redistribution of rare earth elements, niobium, phosphorus, barium, strontium, uranium, thorium, and associated critical minerals, thereby making Indian carbonatites one of the country's most significant geological resources for future strategic mineral exploration and development.

PETROGENESIS AND MAGMATIC EVOLUTION

The origin of carbonatite magmas has remained one of the most extensively debated topics in igneous petrology. However, geological, petrographic, geochemical, isotopic, experimental, and geochronological investigations carried out on Indian alkaline–carbonatite complexes over the past several decades have established that these rocks are products of mantle-derived carbonatitic magmatism modified by complex magmatic and post-magmatic processes.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

Although individual complexes exhibit differences in lithology, mineralogy, age, and tectonic setting, they collectively demonstrate a consistent evolutionary history. The different petrogenesis process and associated geological evidences are listed in Table 1. Such processes collectively controlled the formation of economically significant REE and Nb deposits that are increasingly important for India's future critical mineral security (Krishnamurthy, 2019; Randive & Meshram, 2020; Paul et al., 2020; Upadhyay et al., 2021; Aranha et al., 2022; Mohanty et al., 2026).

Geochemical and isotopic studies indicate that the parental magmas of Indian carbonatites originated from low-degree partial melting of volatile-rich, metasomatized subcontinental lithospheric mantle. Mantle metasomatism enriched the source region in incompatible trace elements such as REEs, Nb, Ba, Sr, Th, U, P, and F, thereby generating carbonatitic melts with exceptionally high concentrations of these elements. The widespread occurrence of alkaline silicate rocks in association with carbonatites suggests that both magma types were generated from closely related mantle sources during progressive mantle melting under extensional tectonic conditions (Kumar et al., 1998; Miyazaki et al., 2000; Ackerman, 2017; Krishnamurthy, 2019; Paul et al., 2020).

The close spatial and temporal association between carbonatites and alkaline silicate rocks throughout India strongly supports their comagmatic origin. Most alkaline–carbonatite complexes comprise pyroxenites, syenites, ijolites, nepheline syenites, dunites, gabbros, and fenites that occur together with carbonatites in ring complexes, plugs, dykes, and vein systems. Field relationships indicate repeated magma injections and multiple intrusive phases rather than emplacement during a single magmatic event. Similar intrusive sequences have been documented from the Sevathur, Samalpatti, Hogenakkal, Pakkanadu, Kamthai, Amba Dongar, Sung Valley, and Newania complexes (Subramaniam et al., 1978; Natarajan et al., 1994; Miyazaki et al., 2000; Krishnamurthy, 2019).

Fractional crystallization represents one of the principal mechanisms controlling the evolution of Indian carbonatitic magmas. Progressive crystallization of pyroxene, olivine, amphibole, feldspar, apatite, magnetite, and carbonate minerals continuously modified melt composition, producing a wide spectrum of carbonatite varieties ranging from calcitic to dolomitic and ankeritic compositions. Variations in mineral chemistry, zoning of pyrochlore, apatite compositions, carbonate replacement textures, and systematic changes in trace element abundances all indicate prolonged fractional crystallization during magma evolution (Viladkar & Subramanian, 1995; Srivastava, 1998; Schleicher, 2019; Mohanty et al., 2026).

Carbonate–silicate liquid immiscibility is another important process responsible for the evolution of Indian alkaline–carbonatite complexes. Geological and geochemical evidence suggests that carbonatitic and alkaline silicate magmas separated from a common parental magma during differentiation, producing coexisting carbonate-rich and silicate-rich melts. This process explains the intimate association of carbonatites with syenites, pyroxenites, and ijolites, as well as the complementary geochemical characteristics observed between carbonate and silicate rocks. Several Indian studies have proposed that immiscibility played a major role in the development of the Hogenakkal, Sevathur, Samalpatti, and related complexes, where successive pulses of carbonate-rich magma intruded earlier silicate bodies (Natarajan et al., 1994; Viladkar & Subramanian, 1995; Krishnamurthy, 2019).

Repeated magma replenishment and multistage intrusion further contributed to the complexity of Indian carbonatite complexes. Petrographic relationships, structural observations, and isotopic evidence indicate that many complexes were emplaced through successive intrusive events separated by periods of cooling, alteration, and renewed magmatism. The occurrence of cross-cutting carbonatite veins, multiple generations of carbonate minerals, zoned intrusions, and contrasting isotopic signatures demonstrates prolonged magmatic activity over considerable geological time. Such multistage evolution has been documented particularly in the Sevathur, Samalpatti, Pakkanadu, Hogenakkal, and Newania complexes (Schleicher et al., 1997; Schleicher et al., 1998; Rapprich et al., 2017).

Fenitization is one of the most distinctive metasomatic processes associated with Indian alkaline–carbonatite complexes. During emplacement of carbonatitic magma, alkali-rich hydrothermal fluids extensively altered the surrounding country rocks, producing mineralogical and chemical changes collectively referred to as fenitization. The development of alkali feldspar, aegirine, riebeckite, sodic amphiboles, biotite, carbonate minerals, and other alkali-rich phases within the country rocks reflects intense fluid–rock interaction.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

Fenitization not only records the movement of carbonatitic fluids but also provides valuable evidence for the evolution of alkaline magmatic systems (Subramaniam et al., 1978; Ramasamy, 2012; Subramani, 2017).

Hydrothermal alteration represents the final major stage of carbonatite evolution and has profoundly influenced the mineralogy and economic potential of Indian carbonatites. After emplacement and crystallization, late-stage hydrothermal fluids circulated through fractures and permeable zones, modifying primary mineral assemblages and redistributing incompatible elements. These fluids promoted replacement of pyrochlore, apatite, magnetite, and carbonate minerals while precipitating secondary REE-bearing minerals including bastnäsite, monazite, synchysite, parisite, ancylite, cerianite, and barite. Such hydrothermal processes significantly upgraded the concentrations of REEs and niobium in several Indian deposits (Magna et al., 2020; Upadhyay et al., 2021; Viladkar & Sorokhtina, 2021; Mahapatro et al., 2023; Mohanty et al., 2026).

Supergene weathering further modified many carbonatite complexes through oxidation, dissolution, and secondary enrichment. Tropical weathering conditions promoted decomposition of primary carbonate minerals and concentration of resistant accessory minerals such as pyrochlore, monazite, magnetite, zircon, and apatite within residual soils. In several Indian carbonatite provinces, residual enrichment has considerably increased the economic grade of rare earth element and niobium mineralization, emphasizing the importance of weathering processes in resource development (Krishnamurthy et al., 2000; Krishnamurthy, 2019; Randive & Meshram, 2020).

Overall, the petrogenetic evolution of Indian alkaline–carbonatite complexes reflects a dynamic interaction between mantle-derived magmatism and crustal processes operating over a prolonged geological history. Their remarkable enrichment in incompatible trace elements and critical minerals is the direct consequence of successive magmatic differentiation and fluid-mediated enrichment processes. Consequently, these complexes not only provide important insights into the evolution of the subcontinental lithospheric mantle beneath India but also constitute one of the country's most promising geological resources for rare earth elements, niobium, phosphorus, and other strategic minerals required for future technological and industrial development.

Table 1. Petrogenetic processes and geological evidence

Process	**Geological evidence**	**Reference**
Mantle metasomatism Enriched	Sr–Nd isotopes	Krishnamurthy (2019)
Partial melting	Trace element enrichment	Natarajan et al. (1994)
Fractional crystallization	Mineral zoning	Viladkar & Subramanian (1995)
Liquid immiscibility	Carbonatite–silicate association	Krishnamurthy (2019)
Fenitization	Alkali alteration	Subramaniam et al. (1978)
Hydrothermal alteration	Secondary REE minerals	Mohanty et al. (2025)
Supergene enrichment	REE accumulation	Randive & Meshram (2020)

ECONOMIC AND CRITICAL MINERAL RESOURCES

The increasing global demand for rare earth elements (REEs) and other critical minerals has significantly enhanced the strategic importance of Indian alkaline–carbonatite complexes. These complexes constitute one of the principal primary sources of REEs, niobium (Nb), phosphorus (P), barium (Ba), strontium (Sr), uranium (U), thorium (Th), fluorine (F), titanium (Ti), and zirconium (Zr), all of which are indispensable for renewable energy technologies, electric vehicles, permanent magnets, aerospace, defence systems, electronics, catalysts, and advanced manufacturing industries. Consequently, Indian carbonatites have become major targets for geological investigation and mineral exploration owing to their potential to contribute substantially to the country's critical mineral security (Krishnamurthy et al., 2000; Balaram, 2019; Singh, 2020).

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

The enrichment of REEs in Indian carbonatites primarily results from mantle-derived magmatism followed by prolonged magmatic differentiation and hydrothermal reworking. Rare earth elements behave as highly incompatible elements during mantle melting and progressively concentrate within residual carbonatitic melts during fractional crystallization. Subsequent hydrothermal alteration and fluid-assisted remobilization further upgrade REE concentrations through precipitation of secondary rare earth minerals. Consequently, Indian carbonatites commonly exhibit pronounced enrichment of light rare earth elements (LREEs), particularly La, Ce, Nd, and Pr, whereas heavy rare earth elements (HREEs) generally occur in relatively lower concentrations (Krishnamurthy, 2019; Randive & Meshram, 2020).

A variety of REE-bearing minerals have been identified in Indian alkaline–carbonatite complexes. Bastnäsite and monazite constitute the principal rare earth minerals in most deposits and are commonly accompanied by allanite, synchysite, parisite, ancylite, carbocernaite, cerianite, chevkinite, fluorapatite, and britholite-like phases. These minerals occur either as primary magmatic phases crystallized directly from carbonatitic melts or as secondary hydrothermal minerals formed during fluid-mediated alteration of primary carbonate minerals, apatite, and pyrochlore. Their distribution reflects the combined effects of magmatic differentiation, hydrothermal activity, and supergene enrichment (Bhushan & Kumar, 2013; Upadhyay et al., 2021; Mahapatro et al., 2023; Mohanty et al., 2026).

Niobium represents another economically significant commodity associated with Indian carbonatites. It occurs predominantly within pyrochlore, which serves as the principal Nb-bearing mineral throughout most alkaline provinces. Primary pyrochlore typically crystallizes directly from carbonatitic magma and subsequently undergoes extensive hydrothermal and supergene alteration, resulting in compositional zoning and enrichment in REEs, Pb, U, Th, Ti, Ba, and Sr. These alteration processes substantially enhance the economic potential of niobium mineralization, particularly within the Amba Dongar, Kamthai, Sevathur, and Saidiwasan carbonatite complexes (Magna et al., 2020; Viladkar & Sorokhtina, 2021; Dey et al., 2021; Mohanty et al., 2026).

Among the Indian carbonatite provinces, the Amba Dongar alkaline complex of Gujarat represents one of the country's most intensively investigated REE-bearing systems. Geological, mineralogical, and geochemical investigations have documented extensive hydrothermal alteration that transformed primary pyrochlore into REE-rich secondary phases while simultaneously enriching carbonatites in niobium, vanadium, barium, strontium, and light rare earth elements. The occurrence of wakefieldite-(Ce), vanadinite, Sr-rich barite, titanite, and altered pyrochlore clearly demonstrates the importance of hydrothermal fluids in upgrading mineralization after primary magmatic crystallization (Viladkar, 2019; Magna et al., 2020; Viladkar & Sorokhtina, 2021). The Kamthai carbonatite complex of Rajasthan has emerged as one of India's most promising carbonatite-hosted REE deposits. Geological exploration has identified abundant bastnäsite, synchysite, ancylite, parisite, carbocernaite, cerianite, pyrochlore, and apatite associated with calcitic carbonatites. Geochemical investigations reveal exceptionally high concentrations of light rare earth elements together with enrichment of Sr, Ba, Nb, Th, and U. Resource evaluation indicates that Kamthai constitutes a world-class carbonatite-hosted REE deposit with considerable potential for future commercial development. Detailed mineralogical studies further demonstrate that hydrothermal alteration associated with magnetite-to-hematite transformation played a critical role in remobilizing and concentrating rare earth elements within the deposit (Bhushan & Kumar, 2013; Upadhyay et al., 2021; Aranha et al., 2022).

In southern India, the alkaline–carbonatite complexes of Tamil Nadu represent one of the country's most significant REE provinces. The Sevathur, Samalpatti, Pakkanadu, Hogenakkal, Pikkili, and associated complexes contain economically important concentrations of bastnäsite, monazite, pyrochlore, allanite, apatite, zircon, barite, magnetite, and benstonite. Geochemical investigations consistently report enrichment in La, Ce, Nd, Nb, Sr, Ba, and phosphorus together with characteristic light rare earth element enrichment patterns. Several studies indicate that hydrothermal alteration, fenitization, and weathering substantially increased the concentration of REEs and niobium beyond primary magmatic levels, making these complexes attractive exploration targets (Udas & Krishnamurthy, 1970; Viladkar & Subramanian, 1995; Krishnamurthy et al., 2000; Jeyagopal, 2021; Mahapatro et al., 2023). The Pakkanadu carbonatite–alkaline complex has recently attracted considerable attention because of its exceptionally high REE contents and diverse mineral assemblages. Petrographic and mineralogical investigations identified monazite-(Ce), allanite-(Ce), chevkinite-(Ce), pyrochlore, fluorapatite, strontianite, and barite associated with calcitic carbonatites. Whole-rock geochemistry

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

indicates significant enrichment of barium, strontium, and light rare earth elements, with total REE concentrations locally exceeding 30,000 ppm. Petrographic evidence suggests that carbohydrothermal fluids were responsible for extensive remobilization and secondary concentration of REEs after primary magmatic crystallization (Mahapatro et al., 2023).

Similarly, the Saidiwasan sövite carbonatites of Gujarat exhibit remarkable enrichment in REEs, niobium, uranium, thorium, barium, and strontium. Detailed mineral chemistry demonstrates progressive alteration of primary pyrochlore into cation-deficient REE-rich varieties, while apatite records significant substitution of light rare earth elements through britholite-like reactions. Whole-rock geochemical data reveal extreme enrichment in La, Ce, Nb, Ba, and Th, confirming the high exploration potential of these carbonatites (Mohanty et al., 2026). In northeastern India, the Sung Valley and Samchampi carbonatite complexes constitute important repositories of REEs, apatite, pyrochlore, fluorite, barite, and associated critical minerals. Together with the alkaline provinces of Rajasthan, Gujarat, and Tamil Nadu, these deposits represent important components of India's future rare earth resource base and have attracted increasing interest for strategic mineral exploration (Krishnamurthy et al., 2000; Balaram, 2019; Krishnamurthy, 2019).

Apart from REEs and niobium, Indian carbonatites host economically significant concentrations of phosphate minerals, particularly apatite, which represents an important source of phosphorus for fertilizer production. Magnetite, barite, vermiculite, fluorite, zircon, titanium-bearing minerals, uranium, thorium, and strontium minerals further enhance the economic significance of these complexes. The coexistence of multiple critical mineral commodities within a single carbonatite system substantially improves the feasibility of integrated mineral resource development (Krishnamurthy et al., 2000; Singh, 2020).

Indian alkaline–carbonatite complexes represent one of the country's most valuable geological resources for rare earth elements and associated critical minerals. Their exceptional enrichment in LREEs, niobium, phosphorus, barium, strontium, uranium, thorium, and related commodities reflects a combination of mantle-derived magmatism and subsequent alteration processes operating over prolonged geological time. With the rapidly increasing demand for strategic minerals driven by clean energy technologies and advanced manufacturing, systematic exploration and sustainable development of India's carbonatite-hosted mineral resources will play an increasingly important role in achieving national resource security and supporting future technological growth. The carbonatite complexes of Tamil Nadu constitute important to India's most promising provinces for rare earth elements and associated critical minerals. Bastnäsite, monazite, allanite, pyrochlore, apatite, barite, zircon, magnetite, fluorapatite, and benstonite collectively represent significant economic resources. Geochemical investigations consistently demonstrate enrichment of light rare earth elements together with niobium, phosphorus, barium, strontium, uranium, and thorium, highlighting the strategic importance of these complexes for future mineral exploration (Krishnamurthy et al., 2000; Balaram, 2019; Jeyagopal, 2021; Mahapatro et al., 2023).

Recent advances in mineral exploration, including hyperspectral remote sensing, airborne geophysics, high-resolution geochemistry, isotope geology, machine learning, and mineral systems modelling, have considerably improved the identification of prospective carbonatite-hosted REE deposits in India. Mineral prospective modelling has identified the Kamthai–Sarnu–Dandali region of Rajasthan, the Amba Dongar alkaline province of Gujarat, the alkaline complexes of Tamil Nadu, and the northeastern carbonatite provinces as priority exploration targets for future resource development (Balaram, 2019; Aranha et al., 2022). The overall resource of economic and critical minerals associated with Indian alkaline carbonatite complex are presented in table 2.

Table 2. Alkaline Carbonatite complexes and Economic minerals in India

Complex	Geological Age	Associated Rocks	Principal Minerals	Economic Minerals & Elements
Amba Dongar (Gujarat)	Cretaceous (65.0 ± 0.3 Ma)	Calcite, dolomite, ankerite carbonatites, alkaline silicate	Calcite, dolomite, ankerite, fluorite, pyrochlore, bastnäsite, wakefieldite-(Ce),	Bastnäsite, pyrochlore, fluorite, wakefieldite-(Ce), vanadinite / REEs

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

		rocks, basaltic association	vanadinite, Sr-barite, titanite	(LREE), Nb, F, V, Ba, Sr
Kamthai (Rajasthan)	Cretaceous / Tertiary (68.57 ± 0.8 Ma)	Carbonatites associated with Malani igneous suite	Bastnäsite, synchysite, ancylite, parisite, carbocernaite, cerianite, pyrochlore, apatite, hematite	Bastnäsite, synchysite, ancylite, parisite, carbocernaite, pyrochlore, apatite / REEs (La, Ce, Nd), Nb, Sr, Ba, Th, U
Sarnu–Dandali (Rajasthan)	Cretaceous (68.57 ± 0.8 Ma)	Alkaline suite, carbonatites, associated volcanic/ subvolcanic rocks	Carbonates, feldspers, pyroxenes, REE-bearing accessory minerals	Bastnäsite, ancylite, pyrochlore, apatite / REEs, Nb, Sr, Ba
Mundwara (Rajasthan)	Cretaceous (68.53 ± 0.16 Ma)	Carbonatites, ijolites, nepheline syenites, gabbros	Calcite, dolomite, silicates, accessory rare-metal phases	REE minerals, apatite / REEs, P, Sr, Ba
Newania (Rajasthan)	Precambrian (Paleoproterozoic/Neoproterozoic)	Dolomitic carbonatites, fenitized basement gneisses	Dolomite, apatite, phlogopite, magnetite, pyrochlore	Apatite, pyrochlore / P, Nb, REEs
Samalpatti (Tamil Nadu)	Neoproterozoic (700 ± 30 Ma)	Calcic/dolomitic carbonatites, pyroxenites, syenites, fenites, ultramafic rocks	Calcite, dolomite, apatite, amphibole, pyroxene, barite, magnetite, pyrochlore, benstonite	Monazite, benstonite, apatite, pyrochlore / REEs, Ba, Sr, Nb, P
Sevathur (Tamil Nadu)	Neoproterozoic (767.0 ± 8 Ma and 801 ± 11 Ma)	Calcic/dolomitic carbonatites, pyroxenites, syenites, ijolites, fenites, ultramafic rocks	Calcite, dolomite, aegirine, biotite, amphibole, apatite, magnetite, pyrochlore, bastnäsite, monazite	Bastnäsite, monazite, pyrochlore, apatite, magnetite / REEs, Nb, P
Pakkanadu (Tamil Nadu)	Neoproterozoic (771 ± 2 Ma and 599 ± 30 Ma)	Calcitic carbonatites, alkaline silicate rocks	Monazite-(Ce), allanite-(Ce), chevkinite-(Ce), fluorapatite, pyrochlore, strontianite, barite, zircon, magnetite	Monazite, allanite, chevkinite, pyrochlore, fluorapatite / REEs (La, Ce, Nd), Ba, Sr, Nb, P
Pikkili (Tamil Nadu)	Neoproterozoic (2273 ± 13 Ma and 1551 ± 46 Ma)	Carbonatites, pyroxenites, syenites, fenites	Carbonate minerals, pyroxenes, amphiboles, accessory phases	Apatite, accessory REE/Nb minerals / REEs, P, Nb
Hogenakkal (Tamil Nadu)	Paleoproterozoic (2436 ± 154 Ma)	Carbonatites, pyroxenites, syenites, fenitized country rocks	Calcite, dolomite, apatite, amphibole, pyroxene, accessory REE phases	Apatite, REE-bearing phases / P, REEs, Ca, Ba, Sr, Nb

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

Sung Valley (Meghalaya)	Cretaceous (107.2 ± 0.8Ma and 106 ± 11 Ma)	Carbonatites, pyroxenites, peridotites, ijolites, nepheline syenites	Calcite, dolomite, apatite, pyrochlore, monazite, bastnäsite, fluorite, phlogopite	Monazite, bastnäsite, apatite, pyrochlore, fluorite / REEs, P, Nb, F
Samchampi (Meghalaya)	Cretaceous (105 Ma)	Carbonatites, pyroxenites, alkali gabbros, syenites	Carbonate minerals, apatite, pyrochlore, REE-bearing phases	Apatite, pyrochlore, REE phases / P, Nb, REEs

References: Udas & Krishnamurthy (1969); Krishnamurthy (2019); Srivastava & Taylor (1996) Natarajan et al. (1994); Mahapatro et al. (2023); Viladkar (2019); Upadhyay et al. (2021); Balaram (2019).

Overall, the alkaline–carbonatite complexes of Tamil Nadu provide an outstanding record of mantle-derived magmatism, tectonic evolution, hydrothermal alteration, and critical mineral enrichment within the Southern Granulite Terrain. Their geological diversity, well-preserved magmatic features, and exceptional concentrations of rare earth elements and associated strategic minerals make them indispensable for understanding the evolution of alkaline magmatism in Peninsular India while simultaneously representing one of the country's most prospective regions for future critical mineral exploration.

CONCLUSION

Indian alkaline–carbonatite complexes constitute one of the most significant manifestations of mantle-derived alkaline magmatism within the Precambrian shield and represent an invaluable geological archive for understanding mantle evolution, continental tectonics, magmatic differentiation, and critical mineral enrichment. Geological, petrographic, mineralogical, geochemical, isotopic, and geochronological investigations consistently indicate that Indian carbonatites originated through low-degree partial melting of a metasomatized subcontinental lithospheric mantle followed by various alteration processes. The combined influence of these processes produced the remarkable lithological diversity and exceptional concentrations of incompatible elements that characterize Indian carbonatite complexes. The major alkaline–carbonatite provinces of India, collectively host significant resources of rare earth elements, niobium, phosphorus, barium, strontium, uranium, thorium, and associated strategic minerals.

With the accelerating global transition towards renewable energy technologies, the demand for rare earth elements and other critical minerals is expected to increase substantially in the coming decades. Indian alkaline–carbonatite complexes therefore represent strategic national resources capable of contributing significantly to domestic supply chains for critical minerals. Continued multidisciplinary research, systematic exploration, resource evaluation, and sustainable mineral development will be essential for realizing the full economic potential of these complexes while simultaneously advancing scientific understanding of alkaline magmatism and mantle processes. The high resolution geochronological investigations should be expanded to establish precise emplacement ages and the temporal evolution of Indian alkaline–carbonatite complexes. Such data are particularly needed for the alkaline province in SGT, where several complexes still lack robust geochronological information.

The application of modern exploration technologies, including hyperspectral remote sensing, airborne geophysics, machine learning, mineral proceptivity modelling, and three-dimensional geological modelling, offers significant opportunities for discovering concealed carbonatite-hosted REE deposits. Integration of these approaches with conventional geological mapping and geochemical exploration is expected to improve exploration efficiency and resource evaluation across the major alkaline provinces of Tamil Nadu, Rajasthan, Gujarat, and north-eastern India.

ACKNOWLEDGEMENT

We authors thankful to the Department of Science and Technology (DST), New Delhi for funding a research project (Sanction order: BDID/01/23/2014-HSRS). Mr. S. Ranjitkumar expresses his gratitude to the DST for

providing the Research fellowships and also acknowledges Periyar University for supporting URF during his partial research period.

REFERENCE

1. Ackerman, L., Magna, T., Rapprich, V., Upadhyay, D., Krátký, O., Čejková, B., Erban, V., Kochergina, Y. V., & Hrstka, T. (2017). Contrasting petrogenesis of spatially related carbonatites from Samalpatti and Sevattur, Tamil Nadu, India. Lithos, 284, 257–275. https://doi.org/10.1016/j.lithos.2017.03.029
2. Aranha, M., Porwal, A., Sundaralingam, M., González-Álvarez, I., Markan, A., & Rao, K. (2022). Rare earth elements associated with carbonatite–alkaline complexes in western Rajasthan, India: exploration targeting at regional scale. Solid Earth, 13(3), 497-518.
3. Balaram, V. (2019). Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geoscience Frontiers, 10(4), 1285–1303. https://doi.org/10.1016/j.gsf.2018.12.005
4. Bhushan, S. K., & Kumar, A. (2013). First carbonatite hosted REE deposit from India. Journal of the Geological Society of India, 81(1), 41-60.
5. Dey, M., Bhattacharjee, S., Chakrabarty, A., Mitchell, R. H., Pal, S., Pal, S., & Sen, A. K. (2021). Compositional variation and genesis of pyrochlore, belkovite and baotite from the Sevattur carbonatite complex, India. Mineralogical Magazine, 85(4), 588–606. https://doi.org/10.1180/mgm.2021.37
6. Jeyagopal, A. V. (2021). Geological Perspectives of Rare Earth Elements in India with a Special Reference to Tamilnadu: A Review. Journal of Chennai Academy of Sciences, 3(1), 57-65.
7. Krishnamurthy, P. (2019). Carbonatites of India. Journal of the Geological Society of India, 94(2), 117–138. https://doi.org/10.1007/s12594-019-1281-y
8. Krishnamurthy, P., Hoda, S. Q., Sinha, R. P., Banerjee, D. C., & Dwivedy, K. K. (2000). Economic aspects of carbonatites of India. Journal of Asian Earth Sciences, 18(2), 229–235. https://doi.org/10.1016/S1367-9120(99)00031-0
9. Kumar, P. S., Parthasarathy, G., Das Sharma, S., Srinivasan, R., & Krishnamurthy, P. (2001). Mineralogical and geochemical study on carbonate veins of the Salem-Attur fault zone, Southern India: Evidence for carbonatitic affinity. Journal of the Geological Society of India, 58(1), 15-26.
10. Kumar, S. N. C., Gopalan, K., & Macdougall, J. D. (1998). A long-lived enriched mantle source for two Proterozoic carbonatite complexes from Tamil Nadu, southern India. Geochimica et Cosmochimica Acta, 62(3), 515–523. https://doi.org/10.1016/S0016-7037(97)00341-4
11. Magna, T., Viladkar, S., Rapprich, V., Pour, O., Hopp, J., & Čejková, B. (2020). Nb–V-enriched sövites of the northeastern and eastern part of the Amba Dongar carbonatite ring dike, India–a reflection of post-emplacement hydrothermal overprint?. Geochemistry, 80(1), 125534.
12. Mahapatro, S. N., Meshram, T., & Korakappa, M. (2023). Mineralogy of Pakkanadu carbonatites and associated rocks, South India: constraints on evolution and evidences for REE enrichment: SN Mahapatro et al. Mineralogy and Petrology, 117(3), 595-617.
13. Meshram, T., & Randive, K. (2024). Olivine composition of calcite-carbonatite from Sevvattur carbonatite alkaline complex, Dharmapuri Rift Zone, Southern Granulite Terrain, India. Geosystems and Geoenvironment, 3(4), 100235. https://doi.org/10.1016/j.geogeo.2023.100235
14. Miyazaki, T., Kagami, H., Shuto, K., Morikiyo, T., Mohan, V. R., & Rajasekaran, K. C. (2000). Rb–Sr geochronology, Nd–Sr isotopes and whole-rock geochemistry of Yelagiri and Sevattur syenites, Tamil Nadu, South India. Gondwana Research, 3(1), 39–53. https://doi.org/10.1016/S1342-937X(05)70056-3
15. Mohanty, S., Sahoo, H. S., Viladkar, S., Chatterjee, C., Mundra, K. L., & Ghatak, A. (2026). Insights to Pyrochlore and Apatite Evolutionary Trends: Constraints From Mineral and Bulk Chemistry of Saidiwasan Sövites, Gujarat, India. Geological Journal, 61(4), 1081-1104.
16. Natarajana, M., Rao, B. B., Parthasarathy, R., Kumar, A., & Gopalan, K. (1994). 2.0 ga old pyroxenite-carbonatite complex of Hogenakal, Tamil Nadu, south India. Precambrian Research, 65(1-4), 167-181.
17. Pandit, M. K., Sial, A. N., Sukumaran, G. B., Pimentel, M. M., Ramasamy, A. K., & Ferreira, V. P. (2002). Depleted and enriched mantle sources for Paleo- and Neoproterozoic carbonatites of southern India: Sr, Nd, C–O isotopic and geochemical constraints. Chemical Geology, 189(1–2), 69–89. https://doi.org/10.1016/S0009-2541(02)00136-5

18. Paul, J., Chandra, J., & Halder, M. (2020). Proterozoic alkaline rocks and carbonatites of Peninsular India: A review. Episodes, 43(1), 249–277. https://doi.org/10.18814/epiiugs/2020/020015
19. Ramasamy, R. (2012). Crystallization, Fractionation and Solidification of Co-Magmatic Alkaline Series Sequentially Emplaced in the Carbonatite Complex of Tiruppattur, Tamil Nadu, India. In Crystallization-Science and Technology. IntechOpen.
20. Ramasamy, R., Gwalani, L. G., & Subramanian, S. P. (2001). A note on the occurrence and formation of magnetite in the carbonatites of Sevvattur, North Arcot District, Tamil Nadu, Southern India. Journal of Asian Earth Sciences, 19(3), 297–304. https://doi.org/10.1016/S1367-9120(00)00046-8
21. Randive, K., & Meshram, T. (2020). An overview of the carbonatites from the Indian subcontinent. Open Geosciences, 12(1), 85–116.
22. Rapprich, V., Pecskay, Z., Magna, T., & Mikova, J. (2017, August). Age disparity for spatially related Sevattur and Samalpatti carbonatite complexes. In Twenty-seventh Annual Goldschmidt Conference (p. 3280).
23. Ray, J. S., & Parthasarathy, G. (2019, June). Recent Advancement in Studies of Deccan Trap and Its Basement; Carbonatites and Kimberlites–An Indian Perspective in Last Five Years. In Proc. Indian Natl. Sci. Acad. (Vol. 85, No. 2), pp. 481-492).
24. Schleicher, H. (2019). In situ determination of trace element and REE partitioning in a natural apatite–carbonatite melt system using synchrotron XRF microprobe analysis. Journal of the Geological Society of India, 93(3), 305–312. https://doi.org/10.1007/s12594-019-1178-9
25. Schleicher, H., Kramm, U., Pernicka, E., Schidlowski, M., Schmidt, F., Subramanian, V., Todt, W., & Viladkar, S. G. (1998). Enriched subcontinental upper mantle beneath southern India: Evidence from Pb, Nd, Sr, and C–O isotopic studies on Tamil Nadu carbonatites. Journal of Petrology, 39(10), 1765–1785. https://doi.org/10.1093/petroj/39.10.1765
26. Schleicher, H., Todt, W., Viladkar, S. G., & Schmidt, F. (1997). Pb/Pb age determinations on the Newania and Sevattur carbonatites of India: Evidence for multi-stage histories. Chemical Geology, 140(3–4), 261–273.
27. Semenov, E. I., Gopal, V., & Subramanian, V. (1971). A note on the occurrence of benstonite, a carbonate of calcium and barium from the carbonatite complex at Jogipatti, near Samalpatti, Dharmapuri District, Tamil Nadu. Current Science, 254-256.
28. Singh, Y. (2020). Strategic and critical element potential of Indian carbonatites. J Geosciences Res, 5(2), 161-170.
29. Srivastava, R. K. (1998). Petrology of the Proterozoic alkaline carbonatite complex of Samalpatti, District Dharmapuri, Tamil Nadu. Journal of the Geological Society of India, 51(2), 233–244. https://www.geosocindia.org/index.php/jgsi/article/view/68898
30. Srivastava, R. K., & Taylor, L. A. (1996). Carbon and oxygen isotope variations in Indian carbonatites. International Geology Review, 38(5), 419–429. https://doi.org/10.1080/00206819709465344
31. Subramani, R (2017). Distribution and Petrochemical Patterns of Carbonatites-Alkaline Complex of Samalpatti, Dharmapuri District, Tamilnadu, India. International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081 2017 Vol. 7 (2) May-August, pp. 70-76
32. Subramaniam, V., Viladkar, S. G., & Upendran, R. (1978). Carbonatite alkali complex of Samalpatti, Dharmapuri District, Tamil Nadu. Journal of the Geological Society of India, 19(5), 206–216. https://doi.org/10.17491/jgsi/1978/190502
33. Udas, G. R., & Krishnamurthy, P. (1969). Carbonatites of Sevathur and Jokipatti, Madras State, India (No. CONF-681088--6). Univ. of Saugar, India.
34. Upadhyay, D., Mondal, S., Patel, A. K., Mishra, B., Pruseth, K. L., & Bhushan, S. K. (2021). Rare earth element precipitation induced by non-redox transformation of magnetite to hematite: Microtextural and geochemical evidence from the Kamthai carbonatite complex, western India. Lithos, 400, 106381.
35. Viladkar, S. G. (2019). Silico-carbonatite vs silicified carbonatite in Amba Dongar carbonatite diatreme, Gujarat, India.
36. Viladkar, S. G., & Sorokhtina, N. V. (2021). Evolution of pyrochlore in carbonatites of the Amba Dongar complex, India. Mineralogical Magazine, 85(4), 554-567.
37. Viladkar, S. G., & Subramanian, V. (1995). Mineralogy and geochemistry of the carbonatites of the Sevathur and Samalpatti complexes, Tamil Nadu. Journal of the Geological Society of India, 45(5), 505–517. https://doi.org/10.17491/jgsi/1995/450502

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

38. Vladykin, N. V., Viladkar, S. G., Miyazaki, T., & Mohan, V. R. (2008). Geochemistry of benstonite and associated carbonatites of Sevathur, Jogipatti and Samalpatti, Tamil Nadu, South India, and Murun Massif, Siberia. Journal of the Geological Society of India, 72(3), 312–324. https://doi.org/10.17491/jgsi/2008/720303