# RARE-EARTH EXPLORATION IN INDIA

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## INTRODUCTION

A groupof 15 geochemically coherent metallic elements are named as "rare-earths" by the International Union of Pure and Applied Chemistry (IUPAC). On account of similar geochemical properties, Scandium (Sc) and Yttrium (Y) are also grouped with rare-earths by IUPAC. All the rare-earths [atomic numbers 57 (La) to71 (Lu)] occurinnature, except promethium (Pm). After initial discovery and extraction,rare earth element (REE) uses have substantially moved upwards to high-purity separated rare earth metals finding applications in advanced electronics,lighting, power generation and military applications. Accordingly, requirement forREEprogressively moved up. In advanced countries, REEare essential to several industrial, commercial and residential appliances and in the increasing electrification ofvehicles. AlthoughREEmayonlybe required in a very less amounts, they will impart life to certain products, rendering them difficult to replace (SmithStegen,2015). In the forthcoming 10 years, major requirement for REEis expected for manufacturing of hybridelectricvehicles(HEVs)andfull electricvehicles(EVs) that will need substantial amount of REE (Weng et al. 2015; Goodenough et al. 2017).HEVsand EVs anticipated growth is from2.3 million units in2016 to over10.1million units in2026(Roskill2016). The accentuated growthislikelyto increase the requirement of neodymium-iron-boron (NdFeB)magnets.Also, another usage of NdFeBmagnets is inrenewableenergygeneration, whichwould become gradually imperative , as governments and industries aim to fulfil stringentclimatechangeandemissionsstandards (Weng et al. 2015; Goodenough et al. 2017). Today's high-tech world is governed by REE, that are considered essential for achieving sustainable development targets (Bertinelli et al.

2019).In this article, an overview of geologic sources and exploration of REE in India is briefly outlined.

## GEOLOGIC SOURCES

Rare-earth sources are categories into several types with genetic links to igneous, sedimentaryand secondary processes of formation (O'Callaghan, 2012). Various sources are carbonatites, (per)alkaline granites, hydrothermal veins andpegmatites, quartz-pebble conglomerate,stream placers and beach sands, residual / supergeneweathering, ion adsorptionclays, iron-oxide copper-gold type, and other types (Singh, 2020a).Salient features of only prominent Indian sources (Fig. 1) are given below.

**Carbonatites**: The term 'carbonatite' is used for carbonate rocks of igneous origin with >50% modal carbonate of magmatic origin and <20 wt.% $SiO_2$(Le Maitre, 2002).Carbonatite-hosted deposits comprise the most important rare-earth resource globally, especially for thelightrare-earths, constituting between5and15 wt.%REO. The carbonatite of Amba Dongar in Gujarat revealed about 25.70 million tonnes of ore containing 3.46 lakh tonnes REO, whereas carbonatite complex at Kamthai in Rajasthan contains 7.36 million tonnes ore with average grade of 1.62% REO (Singh, 2019, 2020a, b). In north-east India, Samchampi and Sung Valley carbonatites and associated soils contain REE. In south India, carbonatites at Pakkanadu-Mulakkadu-Sevattur revealed significant REE concentrations. Several other carbonatite bodies from other parts of India have analysed elevated contents of strategic and critical elements (Singh, 2020b).

**(Per)alkaline Granites**: Agpaitic rocks deficient in calcium host REE concentrations adequately high enoughto be economically extractable. REO concentration is normally between 1.5 and 2.5 wt.%, which is facilitated by filling of voids by REE in lattice of minerals created by deficiency of calcium (Walters et al.2011). Such rocks form possible significant resource-bases particularly for theheavy REE(HREE).In India, Siwana ring complex in Rajasthan is emerging as potential hard rock source especially for HREE. Preliminary exploration inputs have revealed a cumulative resource of more than one million tonne of REE in the alkaline Siwana Ring Complex, hosted mainly in agpaitic granitoids and rhyolitic tuffs (Varma, 2019; Singh, 2020a, 2021a).

**Hydrothermal Veins**: Hydrothermal deposits are spatially and genetically linked with alkaline granite andcarbonatite intrusions, and may form extensive, structurally-controlled, interconnected network of veins (Chao et al. 1992). Generally, they are between 0.5 and 1,400 m long, with a width between 1 cm and 150 cm (O'Callaghan, 2012). The REE minerals in veins are represented by allanite, apatite, monazite,euxenite, bastnaesite, parisite, synchysite and fluorite, enrichment being linked with greater mobility of REE in aqueous systems (Leroy and Turpin, 1998). Hydrothermal-type deposits/occurrences are known from Singhbhum shear zone, south Purulia shear zone and Eastern Ghats Belt in India. In addition, a 320-km long albitite belt in Western India, Rajasthan revealed occasional occurrences of REE-bearing minerals along with several refractory phases (Singh 2020a).

**Beach Sands**: Rareearth bearing placerdepositsarethe product of weathering,erosion,transportation, sorting and concentration ofmaterial from different types of igneous and metamorphic rocks, with deposition in streams orcoastal settings (Long et al.2010). Nearly 360 placer deposits are known worldwide with Tertiaryand Quaternarycoastalmarinesands (Oris and Grauch, 2002).Coastal placers form most important resources for the recovery of rare-earths, although high thorium content associated with REE minerals of placers has been a discouraging aspect (Walters etal. 2011). The primary rare earth minerals present in the placers include monazite and xenotime. Owing to their presence comparatively as common accessoryminerals in various rocks, they are found in varying concentrations in most of the placerdeposits all over the world (Long et al. 2010). In India, beach placer deposits of commercial importance occur along eastern and southern sea coasts of India (Fig. 1; Singh, 2020a, c).Exploration efforts by employing both routine and innovative drilling and laboratory methods brought to light several heavy mineral placer deposits in different coastal areas (Rajamanickam, 2001; Dhana Raju et al. 2001; Lovson et al. 2005), with variably high concentrations of heavies (Fig. 2). Some inland placer bodies in Kerala, Tamil Nadu, Odisha, Andhra Pradesh, Maharashtra, Gujarat and West Bengal states have also been recognised (Dhana Raju et al. 2001). Someofthecoastline beach placer deposits of India are extensive andrichest, comprising ilmenite,rutile,garnet, monazite,zirconand sillimanite heavy mineral assemblagee. Ilmenite-richmajorbeachanddunesanddeposits are located Kerala(Chavara); TamilNadu(Manavalakurichi,Midalam,Vayakallur); AndhraPradesh;Odisha;andMaharashtra.Theilmenite commonlycontains50- 60%$TiO_2$andis suitable fordifferentprocesstechnologies. Ilmenites from Kerala coast have up to 70% $TiO_2$ on account of conversion of ilmenite to leucoxene (IBM 2018). Zircon, monaziteandsillimaniteconstitutepotentialco-products.

A few beach placer deposits are under exploitation over the last several decades. Mining and beneficiation of beach sand deposits are currently carried out by the IREL (India) Limited, a public sector undertaking of the Department of Atomic Energy, Government of India, and Kerala Mineral and Metals Limited (KMML), a Kerala State Government undertaking (IBM 2018). Abundances of REE-bearing minerals reveal considerable variation in different beach sand deposits (for details see Singh, 2020a).

**Stream Placers**: Inland stream placers are attractive especially for Y and HREE resources. Major stream placer deposits occur in Chhotanagpur granite gneiss complex (CGGC) terrain in Jharkhand and Chhattisgarh. Sizeable REE-bearing placers occur in four streams, namely, Deo, Girma, Halwai and Pojenga in Gumla-Simdega district, Jharkhand. Other streams in CGGC terrain, which contain heavy rare-earth-bearing stream placers of commercial interest, include (i) Siri-Champajharia-Dhob-Baljora rivers in parts of Jashpur district, Chhattisgarh; (ii) Mahan River basin in Surguja-Balrampurdistricts, Chhattisgarh; and (iii) Kanhar river basin around Khoka, Sarpatwa, Amtiyatola, Bhagtaniya and Kota villages in Surguja (Chhattisgarh) and Sonbhadra (Uttar Pradesh) districts(Rai and Banerjee, 1995; Singh, 2020a, 2021a). Substantial deposition of placers is restricted to point bars and side bars and flood plain sediments (Fig. 3). Accumulation of heavy mineral is high in point bars, especially in top 0.5 m of the bars (Singh and Rai, 1992). Some of these placers are also being mined (Fig. 3) for recovering rare-earth minerals.Minor stream placer occurrences are scattered in various regions of India (for details see Singh, 2020a).

**Other Sources**: Economically viable REE concentrations also occur in a range of other geologic domains and lithological associations, e.g., quartz-pebble conglomerates, phosphorites and phosphatic sedimentary rocks, marine phosphates (BGS, 2011). Furthermore, seafloor mud has also been focused as a potential resource of REE(BGS, 2011). Details about these Indian sources are available elsewhere (Singh, 2020a, 2021b).

**Secondary Sources**: Nowadays non-conventional secondary REE resources, especially industrial process residues are also receiving attention as REE sources (Binnemans et al. 2015). In India, some work done has been done to recover REE from various secondary sources (for details see Singh, 2020a; 2021c,d).

## EXPLORATION

The guiding rule for any mineral exploration is to commence from knownand then go to unknown. In this regard, it begins from literature survey to understand gross geological settings and controls of already known deposits, which guides in targeting new areas having similar geological settings. From regional scale,exploration target is gradually narrowed down by integrating results of remote sensing, geophysical, geological, geochemical, mineralogical studies and elemental analysis. As the REE occurrences/deposits known till date from diverse geological environments in India are radioactive due to the presence of uranium and / or thorium in REE-bearing minerals(albeit with the variable range of radioactivity), gamma-ray spectrometry is helpful in locating radioactive areas for follow-up work. Significantly, due to geochemical affinity of U, Th, REE and other high-field strength elements (HFSE) they tend to enrich together especially in successively younger phases of magmatic differentiates of igneous rocks.Accordingly, the investigative methodology, involving multidisciplinary approaches, adopted for exploration of radioactive minerals have some commonalities in initial stages. Once anomaly is picked up, semi-detailed and detailed exploration is undertaken according to nature and type of REE, U, Th, and associated HFSE mineralization specific methods are adopted in resource evaluation involving multidisciplinary approaches. At all stages of exploration, laboratory studies of samples, involving various analytical techniques, are done to know mineralogy, ore genesis, REE abundances, leading to resource estimation. General sequence of exploration adopted for REE is shown (Fig. 4).As far as possible, multi-elemental chemical analyses of mineralised samples should be taken up routinely done. This data would provide opportunity to assess possible recovery of other associated metals as co-products and by-products along with rare-earths, which will reduce cost of production.

## CONCLUSION

The exploration for rare-earths involves multidisciplinary approaches (Fig. 4). While exploration (and commercial exploitation)efforts for beach sand and stream placers are already in progress, searches for rare-earth concentrations have been intensified by exploration agencies in other geological domains, especially carbonatites and alkaline complexes, per(alkaline) felsic bodies, hydrothermal veins and associated weathered profiles.There are vast areas with favourable geological settings in the Indian shield that could be taken up for rare-earth and associated elements exploration on an adjudged priority.

The growth of the REE industry in India needs to have linkage with systematic use of many natural resources in a coordinated way. Large-scale mine (LSM) may be preferred where vast stretches of deposits occur (Fig. 2), whereas artisanal to small-scale mining (ASM) would be appropriate in the case where deposits are of small dimensions and scattered over large area in a region (Fig. 3). Both downstream and upstream sectors should be developed to sustain the REE industry chain. This effort should integrate multidisciplinary expert groups. The REE Industry should form an inseparable part of the *"Atmnirbhar Bharat"* throughMine to Metal to Make in India programme, as envisaged by our Prime Minister of India. In this direction, AMD-IREL-BARC-NFC-DMRL-ARCI-CMAT together can make prominent contributions.

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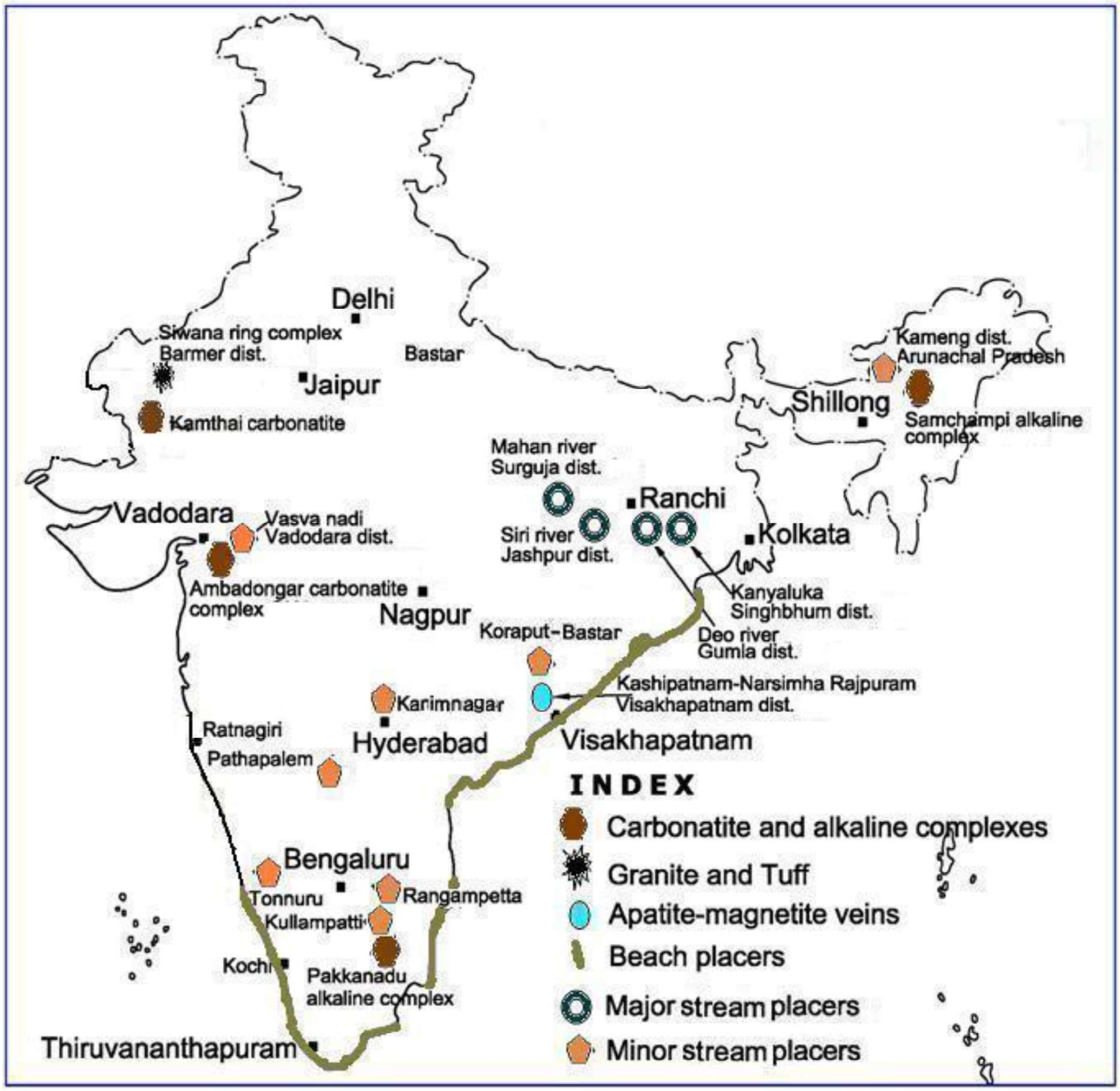



**Fig. 1** Geographical locations of selected REE deposits/occurrences of India (After Singh, 2020a).

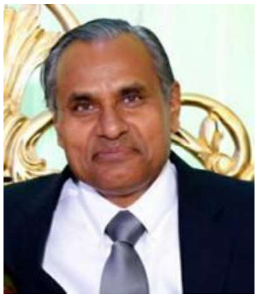
**Fig. 2** Beach sand mineral deposit. Note layers of heavy mineral concentrations (Credit: Deepak Rathod).

**Fig. 3**Partially mined heavy rare-earth-bearing stream placer deposits in central India.

**[For Fig. 4 PDF attached separately]**

**Fig. 4** Sequential flow sheet for exploration of rare-earths in India (Modified after Dhana Raju, 2005; Singh, 2020a)

**Biosketch of Dr. Yamuna Singh**



Dr. Yamuna Singh served over 35 years at AMD, DAE, Govt. of India and retired as Head, MPG Division. He discovered several strategic and critical mineral resources in Central India and Published 160 research papers and 7 Book Chapters. He also edited 16 Volumes of Journals and authored 1 book entitled, "Rare Earth Element Resources: Indian Context, Published by Springer. He is a recipient of several National Awards: (i) National Geoscience Award from Government of India; (ii) S. Narayanswami Award & (iii) Radhakrishna Prize from Geological Society of India; (iv) Prof. S.M. Ramananda Setty Award from Mineralogical Society of India**;** **(v)** Sitaram Rungta Memorial Award from Society of Geoscientists and Allied Technologists, Bhubaneswar; (vi) Master Tanay Chadha Memorial Geologist Award from Mining Engineers' Association of India, and (vii) Hindi Sevi Samman Puraskar from DAE, Govt. of India. He is an elected Fellow of Telangana Academy of Sciences, Hyderabad and Life Fellow/Member of 15 Scientific Societies/Professional Bodies including ISAS. He is President, Indian Association of Applied Geochemists (ISAG), Hyderabad and Expert Member, Commission for Scientific & Technical Terminology, MHRD, Government of India. He is working as Visiting Faculty, University of Hyderabad and Guest Faculty in Geological Survey of India Training Institute, Hyderabad