Chapter 10

The Way Forward

10.1 Introduction

India is endowed with fairly vast resources of rare earth elements (REE). Notwithstanding this, it has not been able to make its niche in global rare earth industry. India's share of rare earth oxide (REO) production is reported to be less than 2% of the total world production (Zangeneh 2018). Nevertheless, with the passage of time spanning from 1950s to 2012, perceptible progress has been made from merely restricting in mining field to achieving capabilities of separating high purity REE (Zangeneh 2018). The India's strength lies in adequate availability of certain individual rare earths, namely, La, Ce, Pr, Nd, Sm, Gd, Y and Dy, that are much needed for making downstream products which have high market values (Singh 2019, 2020). Accordingly, it is imperative to resort to volarisation of these elements. The most prominent intermediate products are permanent magnets that are needed in diverse fields, such as, industrial and consumer electronics, automotive, medical and aerospace (Zangeneh 2018). In addition to use for strategic purposes in aerospace and defence, the fast growths of automobile and electronics industries, and currently sustained thrust for clean energy, have accentuated requirements of more permanent magnets. Prominent global share of NdFeB magnet production is by China and Japan (90%), with some by Europe (Germany, UK and France), USA and Canada (Zangeneh 2018). It is believed that ease of availability of raw materials is the main reason for China's dominance in production amongst Asian countries, whereas Japan imports 82% rare earths from China (Zangeneh 2018). In this chapter, the relative merits and potential of the several REE sources for future development and directions for larger inputs in exploration, on the one hand and the utilization of the industrial sources, on the other have been evaluated in Indian context.

10.2 Commercial Potentials of Indian REE Deposits/Occurrences

The relative commercial potentialities of various Indian REE deposits/occurrences described in preceding chapters are tentatively categorised. Deposits/occurrences, as assessed from existing knowledge, are presented in sequence of deposits of high commercial potential, and then of medium/small/unknown potential in that order (Table 10.1). While this categorisation is purely suggestive, yet certain parameters have been guiding factors in this attempt. Areas where exploration inputs are more with reasonable degree of confidence have been categorised as deposits of “High commercial potential” and may be considered for immediate commercial mining. In certain cases, additional inputs are needed before they are taken up for mining. Other categorisations, e.g., “Medium”, “Small” and “Unknown” are based on mainly some preliminary signatures, like favourable geological settings, anomalous values of one or more than one individual rare earth elements, follow up work, grades of REE values, their dimensions/reserves or a combination of these, with some assumptions. In many cases of “High”, “Medium”, “Small” and “Unknown” resources, data is scanty, fragmentary, and exploration is not done with REE orientation particularly in the last three in decreasing order. Work on the envisaged industrial process residues (secondary) is in initial stages and without further focussed work, commercial recovery of REE cannot be planned. Although available limited results from sea floor bed/mud are quite encouraging, further work is needed. Also, it is kept under special class of natural resources keeping in mind involvement of International Seaboard Authority on United Nations. All classes, especially medium, small and unknown, need adequate exploration inputs and based on the results relative positions of commercial significance can be modified accordingly (Table 10.1). By further exploration work, some of them may be converted into commercially exploitable resources.

The most promising deposits for light rare earths are contained in the beach sands and carbonatite complexes of western India (Fig. 10.1). These are good sources of monazites and bastnaesites and associated minerals rich in light REE (LREE). Inland stream placers in central India, rich in xenotime and some hydrothermal xenotime deposits of SSZ, including Kanyaluka (Fig. 10.1), form good resources of heavy REE (HREE). So these form major immediate targets for commercial exploitation. However, before initiating commercial mining, flowsheet needs to be developed for economic recovery of REE in the case of carbonatite-hosted REE deposits.

Table 10.1 REE deposits—occurrences in India and their tentative relative commercial potential for exploitation

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
<i>High commercial potential</i>							
1	Beach sand	Cluster of deposits around Chavara, Kerala State	Monazite, garnet, zircon	Av. 33.9	565; Ce > La > Nd from monazite	Under exploitation by dredging/beach washing	Heavies upgradation and high tension separation
2	Beach sand	Cluster of deposits in and around/extension areas of Manavalakuruchi, Tamil Nadu	Monazite, garnet, zircon	Av. 0.024	3.7; La > Ce > Nd > Y > Pr > Yb from zircon	Under exploitation by dredging/beach washing	Heavies upgradation and high tension separation
3	Beach sand	Cluster of deposits in and around Chatrapur, Odisha State	Monazite, garnet, zircon	Av. 56.73	33.88; Ce > La ≥ Nd > Sm > Gd from monazite	Under exploitation by dredging/beach washing	Heavies upgradation and high tension separation
4	Beach sand	Deposits in Bhavanapadu-Kalingapatnam-Srikurmam areas, Andhra Pradesh	Monazite, garnet, zircon	Av. 54.2 wt% (Monazite); 0.37 wt% (Garnet)	Av. 44.8; Ce > La > Nd > Sm from Monazite; 0.37; 0.16 Lu > Er > Dy > Gd > Nd from Garnet	Commercially exploitable	Heavies upgradation and high tension separation
5	Stream placer	Deo, Girma, Halwai rivers, Gumla-Simdega district, Jharkhand	Monazite, xenotime, zircon	0.40–10.25	Mixed LREE and HREE, dominated by LREE	Partially mined earlier. Estimated resources: Monazite 550 t, xenotime 56 t	Wet tabling, induced roll magnetic separation at different Kilo Gauss
6	Stream placer	Siri, Champajharia, Baljora rivers, Jashpur district, Chhattisgarh	Monazite, xenotime, zircon		Mixed LREE and HREE, dominated by LREE	Under mining. Estimated resources: Monazite 300 t, xenotime 40 t	Alluvial mining. Wet tabling, induced roll magnetic separation at different Kilo Gauss

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Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
7	Stream placer	Mahan- Kanhar river basin, Sarguja district, Chhattisgarh and Sonbhadra district, Uttar Pradesh	Monazite, xenotime, zircon	1.20–12.32 wt% Ce ₂ O ₃ ; 1.25–4.12 wt% Y ₂ O ₃	Mixed LREE and HREE, dominated by LREE	250 t of xenotime-bearing concentrate estimated; Alluvial mining may be taken up	Hand panning, induced roll magnetic separation at different Kilo Gauss
8	Hydrothermal vein	Kanyaluka-Khadandungri, Singhbhum district, Jharkhand	Xenotime, apatite	52.768 (xenotime)	0.033; Y > Yb > Dy > Er > Gd > Lu from xenotime	600 t xenotime estimated; Commercially exploitable by gravel mining method	Size distribution, heavy media liquid separation study done
9	Carbonatite	Amba Dongar deposit, Baroda district, Gujarat	Bastnaesite, parisite, synchysite, monazite	Av. > 1.0	5.06-80.45; Ce > La > Nd > Pr > Y > Sm	3.46 lakh tonnes REO at average grade of 1.34% REO estimated. Amenable for open pit mining	Preliminary evaluation attempted. Economic viability and REE extraction to be assessed
10	Carbonatite	Kamthai deposit, Barmer district, Rajasthan	Bastnaesite, synchysite, carbocearnite, cerianite, some britholite, monazite	1.62	Ce > La > Nd > Pr > Sm > Eu	Resource estimates 7.36 million tonnes ore. Amenable for open pit mining	Preliminary evaluation attempted. Economic viability and REE extraction to be assessed
<i>Medium commercial potential</i>							
11	Carbonatite	Pakkanadu-Mulakkadu, Salem district, Tamil Nadu	Monazite, bastnaesite, cerianite, allanite	1.22	LREE-rich	Commercial potentiality to be assessed	Beneficiation study to be done

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Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
12	Peralkaline granite	Cluster of occurrences in Siwana Ring Complex, Barmer district, Rajasthan	Allanite, REE silicates, xenotime, monazite	1.72	1.40; Y > La > Nd > La > Gd > Dy > Sm	Inferred resource of 1 million tonne. May be converted into a mineable resource by open pit and/or underground mining	Results of preliminary beneficiation studies encouraging. Economic viability and REE extraction to be assessed
13	Peralkaline granite	Kanigiri granite, Prakasham district, A.P.	Fergusonite, allanite, thorite, bastnaesite, zircon	0.0696	2.55; Ce > Y > La > Nd	REE resource estimation not done	Study with REE orientation to be done
14	Carbonatite	Beldih-Kumi, Purulia district, West Bengal	Monazite, apatite	0.0637	19; Ce > La > Nd (monazite)	Co-product of phosphate mining	–
15	Carbonatite	San Champi deposit, Karbi Anglong district, Assam	Pyrochlore, crandallite, apatite	0.1213	23.8; Ce > La > Gd > Yb	3644 t of Y in 41.88 million tonnes of ore	Floatation and hydrometallurgical route suggested
<i>Small commercial potential</i>							
16	Hydrothermal vein	Kasipatnam, Visakhapatnam district, AP	Fluorapatite, ancyllite, hydroxyl-bastnaesite, monazite, Y-rich mineral, zircon	1.7888	27.17; Ce > La > Pr > Nd & Sm > Y > Gd	Under exploitation for rock phosphate	Preliminary beneficiation study done
17	Hydrothermal vein	South Purulia Shear Zone, West Bengal	Fluorapatite, allanite, monazite, xenotime, zircon	La 0.112%; Ce 0.1825%; Y 0.03%	Ce > La > Y	Under exploitation for rock phosphate	–

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Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
18	Pegmatite	Pegmatite belts of India	Multiple oxides, metamict phases, monazite, allanite, samarskite, fergusonite, euxenite, aeschynite	Highly variable depending on individual minerals	Both LREE and HREE-rich	Commercially exploitable incidental to columbite-tantalite mining	Float ore collected during mining
19	Migmatite leucosome	Jura, Jaurahi, Lekhar, Kudri, Anjangra in Sonbhadra district, U.P.	Metamict phases, monazite, allanite, xenotime, thorite, samarskite, fergusonite, uraninite	Highly variable depending on individual minerals	Both LREE and HREE-rich	Commercially exploitable incidental to uranium mining by mobile unit	—
20	Hydrothermal vein	Albite belt, Western India	Davidite, brannerite, fergusonite, aeschynite, euxenite, betafite, britholite, allanite, chevkinit, tritonite, monazite, xenotime			Commercially exploitable as by-/co-product of U mining	Preliminary beneficiation study done on davidite-rich ore
21	Carbonatite	Samalpatni, Dharampuri district, Tamil Nadu	Bastnaesite, monazite, fergusonite, chevkinit, allanite	8.2	—	—	—
22	Carbonatite	Sung valley, Jaintia Hills, Meghalaya		0.0244-0.0471 Ce; 0.005-0.010 Y	Ce > Y	—	—
23	Carbonatite	Sevattur, North Arcot district, Tamil Nadu	Uranopyrochlore	0.0912	22.24; Ce > La > Y	—	—
24	Bauxite	Visakhapatnam, A.P.	Monazite, iron oxide	TREE up to 0.0467%	Up to 245.0; Ce > La > Nd	—	—

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Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
25	Laterite	Visakhapatnam, A.P.	Iron oxide	TREE up to 0.0093%	Up to 50.89; Ce > La > Nd		
26	Inland placer	Ranchi-Purulia, Jharkhand and West Bengal	Monazite, ilmenite, sillimanite, rutile, zircon	Monazite-rich sand of about 1 m thickness over about 12 km ² area is reported	—	—	—
<i>Unknown commercial potential</i>							
27	Carbonatite	Sirivasan-Nakal, Chhota Udaipur district, Gujarat	Pyrochlore, bastnaesite, monazite, apatite	0.033–0.047% Ce; 0.021–0.03% La; 0.0085–0.01% Y	—	—	—
28	Carbonatite	Panwad-Kawant, Chhota Udaipur district, Gujarat	Pyrochlore	0.02–0.06% Ce; 0.021–0.05% La; 0.003–0.01% Y	—	—	—
29	Stream placer	Goddavari Vanka Stream, Rangampetta, North Arcot District, Tamil Nadu	Xenotime, monazite, allanite, fergusonite, ilmenite, rutile, zircon, garnet	Up to 0.034% Y ₂ O ₃ in and 0.35% Ce ₂ O ₃ in panned concentrates	—	—	Upgradation of Y ₂ O ₃ (1–3.4%) and Ce ₂ O ₃ (3.3–21.8%) revealed by table concentrates
30	Granitic soil	Tonnur-Pandavpura, Hassan and Mandya districts, Karnataka	Monazite, xenotime, ilmenite, rutile, zircon	Up to 1.37% Y ₂ O ₃ in panned concentrates	—	—	Hand panning revealed upto 5% heavies by weight

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Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
31	Granitic-pegmatitic rock	Kullampatti, Salem district, Tamil Nadu	Uraninite, uranothorite, brannerite, allanite, samarskite, fergusonite, zircon, monazite, xenotime, columbite, garnet	Up to 6924 ppm Y in rock	—	—	Separated mineral fraction from table concentrate of rock yielded 10% Y ₂ O ₃
32	Quartz vein/Pegmatite	Mincheri, Raichur district, Karnataka	Yttriofluorite, gadolinite, britholite, cerianite, allanite, monazite, bastnaesite	0.14–19.62% TREE; one sample revealed 25.29% TREE	—	—	—
33	Stream placer	Pathapalem, Mahboobnagar, Telangana	Monazite, xenotime, ilmenite, zircon, garnet	Up to 5.26% Y ₂ O ₃ in panned concentrates	Ce ₂ O ₃ /Y ₂ O ₃ ratio 1.6–9.99	—	Hand panning revealed 0.61–1.46% heavies by weight
34	Stream placers	Dharmawaram, Karimnagar, Telangana	Monazite, xenotime, thorite, zircon, rutile, brookite, ilmenite	Up to 0.40% Y ₂ O ₃ in panned concentrates	—	—	—
35	Stream placers	Ujol-Vasva, Gujarat	Monazite, xenotime, rutile, zircon	0.51–0.96% Y ₂ O ₃	—	—	—
36	Granitic soil	Tirka, Gondia district, Maharashtra	Monazite, xenotime, zircon, rutile	Monazite contains 52.57–63.65% RE ₂ O ₃ and 1.11–3.35% Y ₂ O ₃ ; Xenotime revealed 41.86% Y ₂ O ₃ and 18.72% RE ₂ O ₃	—	—	THM 0.31–34%; bulk sample revealed 5.77% Y ₂ O ₃

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Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
37	Stream placer	Pauri-Tangla, Nagpur district, Maharashtra	Monazite, xenotime	Panned concentrate revealed 3.59% Y ₂ O ₃ and 13.71% Ce ₂ O ₃	—	—	—
38	Stream placers	Bastar-Koraput, Chhattisgarh and Odisha	Monazite, xenotime, ilmenite, zircon	—	—	—	Magnetic separates from Darba yielded 3.59–7.69% Y ₂ O ₃ at 0.45 A and 3–8% Ce ₂ O ₃ in 0.6 A
39	Beach sand	West Bengal coast	Monazite, zircon, ilmenite, garnet, sphene	—	—	—	—
40	Beach sand	Gujarat coast	Monazite	—	—	—	—
41	Stream placer	Kameng river, East Kameng district, Arunachal Pradesh	Monazite, xenotime, zircon, ilmenite, garnet,	—	—	—	Magnetic separation of feed with 0.82% Y ₂ O ₃ yielded 2.4% Y ₂ O ₃
42	Carbonatite	Niwania, Udaipur district, Rajasthan	Radioactive pyrochlore	40–990 ppm La; 220–2690 ppm Ce; 10 ppm Y	—	—	—
43	Carbonatite	Mer-Mundwara, Sirahi district, Rajasthan	—	210–340 ppm La; 330–470 ppm Ce; 50–104 ppm Y	—	—	—

(continued)

Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
44	Alkaline granite	Kumarkunti-Jhamomal, Nuapada district, Odisha	Thorite, allanite, zircon, fersmite	120–1231 ppm Y; 129–1757 ppm La; 453–1876 ppm Ce	–	–	–
45	Alkali granite	Kullapal, West Bengal		233–1683 ppm TREE; 2–150 ppm Y	1–5	–	–
46	Residual granitic soil	Mandalagiri, Garo Hills, Meghalaya	Xenotime, monazite, zircon	–	–	–	–
47	Carbonate complex	Barpung-Jasra, Kurbi-Anglong district, Assam	–	149–471 ppm Ce; 50–1000 ppm Y	–	–	–
48	Fossil placer	East Kameng district, Arunachal Pradesh	Monazite, thorite, rutile, cyrtolite	4857–9261 ppm	5	–	–
49	Phosphorite,	Hirapur-Mardeora, Chhatarpur, M.P.	Fluorapatite	0.47		–	–
50	Iron oxide breccia complex	Kotri-Dingargah belt, central India	Iron oxide	0.045	5.07	–	–
51	Iron oxide breccia complex	Manupatlugadda, Warangal district, Telangana	Iron oxide	1.55	33.43; Y 0.023%	–	–
52	Iron oxide breccia complex	West Sing and Upper Subansiri district, Arunachal Pradesh	Monazite	LREE 0.017–0.0799%; HREE 0.0023–0.0026%	–	–	–
53	Bauxite	Kachehh, Gujarat	Iron oxide	TREE up to 0.037%	Up to 23.98; Ce > La > Nd	–	–

(continued)

Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
54	Pink granite	Kinwat, Nanded and Yeotmal district, Maharashtra	Monazite, allanite, zircon, rutile, apatite, uraninite	3979–6828 ppm TREE	21–130	–	–
55	Peralkaline granite	Dongargh A-type granite, central India	Allanite, zircon, apatite	TREE 0.0358%	17.4; Ce > La > Nd	–	–
56	QPC	Bagiyabahal–Birtola, East India	–	TREE 0.0365%			
57	QPC	Kotra, IOG basin, Western margin of Bonai granite, Jharkhand–Odisha	Monazite, allanite, xenotime	TREE 0.0356%; 0.0041% Y	–	–	–
58	QPC and associated arenites	Chitradurga Group, south India	Monazite, uranothorite, brannerite, zircon	Up to 0.0163% Y	–	–	–
59	Peralkaline granite	Pala Lahara, Eastern India		0.0509	12.8; Ce > La > y>Na	–	–
60	Peralkaline granite	Nongpoh, Meghalaya	Allanite, monazite, zircon, apatite	0.071	13.6; Ce > La > Nd > Y>Sm	–	–
61	Peralkaline granite	Parburi–Geleki, Karbi Hills, Assam		0.3643	109.9; Ce > La > Nd	–	–
<i>Special category natural resources</i>							
	Sea floor bed/mud	Afanasy Nikitin Seamount, Indian Ocean	Iron-oxyhydroxides and phillipsite	TREY 0.213%	5.25; Ce > La > Y>Nd	May have future commercial potential. However, several issues, e.g., marine ecosystem/life imbalance etc., are involved in sea bed mining. Hence commercial mining has to wait	International Seabed Authority (ISA), a UN body, has to grant permission. Feasibility and beneficiation study is to be done

(continued)

Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
<i>Industrial process residues (unknown potential)</i>							
i	Secondary resource	Coal fly ash from Nayeli Lignite fields, Tamil Nadu	–	TREE 0.20%	2.65; Ce > Nd > Y>La	Low grade, but huge quantity is available for processing. Commercial potentiality may take time	Preliminary beneficiation work done
ii	Secondary resource	Phosphoric acid from different Fertiliser plants of India			Order of recovery in extraction Lu > Yb > Er > Y>Dy > Tb	Low grade, but commercially feasible on account of huge phosphoric acid production by fertiliser plants	Extraction work done. Also, as co-product of U recovery from phosphoric acid
iii	Secondary resource	Coal fly ash from Ib Valley, Bhubaneswar, Odisha		TRE 0.0351%	3.3; La > Pr > Gd > Dy	Low grade, but high commercial potential (as huge quantity is available) for processing, subject to development of innovative technology	Work in initial stage

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Table 10.1 (continued)

S. No.	Nature of deposit	Extent of source beds	Major mineral	TREE (wt%)	LREE/HREE ratio	Status of potential for commercial exploitation	Beneficiation methods
iv	Secondary resource	Coal fly ash from Ranigunj coal field, Salanpur, Asansol		TRE 0.0237%	2.7; La > Pr > Gd > Dy	Low grade, but may be of commercial value in future (as huge quantity is available) for processing, subject to development of innovative technology	Work in initial stage
v	Secondary resource	Red mud produced by NALCO, HINDALC, INDAL, etc.	Allanite, dissakisite	Av. 0.01% Gd ₂ O ₃ in red mud from NALCO	Sc, Y, Ce, La	–	Too little work done
vi	Secondary resource	Electronic waste/Urban mine	Unusable fluorescent lamps, phosphors, etc.		Y, Sc	Less commercial scope as of now. May gain momentum in near future	Some work done
vii	Secondary resource	Tin slags from Bastar, Chhattisgarh	–	REE up to 1.00%	–	Small quantity can be recovered from processing slags	Work not done
viii	Secondary resource	Mine tailings and sulfide slags	–	–	–	Small quantity can be recovered from processing slags	Work not done

Fig. 10.1 Geographical locations of selected REE deposits/occurrences of India

10.3 Exploitation, Exploration and REE Resource Augmentation

The highly skewed demand for individual REE is a major challenge for exploitation and exploration. This problem is further compounded by highly variable concentrations of individual REE in natural occurrences. Also, it has to be ensured that places where REE deposits have been identified are politically acceptable to mine and process them in a cost-effective way. While exploitation is under progress, sustained exploration inputs will keep adding up resource-base leading to augmentation of exploitable resources. This cycle has to be maintained in a close-knit seamless chain of activities of the “Indian Rare Earth Industry”, involving all industrial partners.

10.3.1 Beach Sand Deposits

Large deposits contained in beach sands are under mining following beach washing/dredging techniques (Mohapatra 2019a, b), which can be followed for commercial mining of most of the beach placer mineral deposits. The IREL (India) Limited can assess incremental REE requirements by various Industries, Entrepreneurs and Startups and step up production proportionately by taking up commercial mining from other identified deposits. Indigenous mining, processing, extraction, value addition and end-use demand/market should go as a chain. Requirements of LREE by rare earth industry need to be regulated through mining of beach sand deposits keeping in mind production of LREE from stream placer (and future possible LREE production from carbonatite) deposits. Sustained exploration activity should continue to augment beach placer-based REE resources. Inventory of resources mined and left out need to be maintained for long term planning of commercial beach sand mining. Beach placer mining from unauthorised agencies should be checked.

10.3.2 Stream Placer Deposits

Stream placer deposits in central India are being mined by adopting alluvial mining methods including mobile mining (Verma 2019a). Inland stream placer deposits should be mined following existing alluvial mining practices, recovery of preconcentrates and separation of individual REE minerals from preconcentrates following already established flow sheets. Known stream placer occurrences should be investigated by sustained exploration inputs involving systematic surveying, stream/soil sampling, panning and gravity and magnetic beneficiation to convert them to a mineable resources. This effort will help maintaining chain of stream placer commercial mining, processing, extraction and value addition. Since stream placers are main resources of HREE, their mining should have linkage with market demand of HREE and regulated accordingly. In this regard, vein type deposits of Kanyaluka and other small occurrences may prove to be a sweetener as they have higher basket price.

10.3.3 Carbonatite Deposits

Although considerable carbonatite-hosted REE resources have been identified, studies on feasibility and beneficiation are lacking. Accordingly, while exploration for resource augmentation is going on immediate priority should also be given for assessing beneficiation potentialities of each carbonatite-based resources. For planning commercial exploitation of carbonatite-hosted deposits like Amba Dongar and Kamthai (Table 10.1; Fig. 10.1), to begin with, open pit methods have to be planned

keeping in mind results of feasibility and beneficiation studies. Prior to initiating mining, proper flow sheet need to be developed to ensure effective recovery of REE from mined carbonatite ores. Sustained exploration and resource assessment should continue in adjoining carbonatite bodies, including those located in other parts of India. This effort will provide opportunities for initiating feasibility study and planning exploratory-/regular commercial mining in other areas.

10.3.4 Mineralised Peralkaline-Alkaline Felsic Rocks

Peralkaline granite and associated tuff-hosted mineralisation in western India is of special interest in view of substantial HREE concentrations, some of which have more market price (Table 10.2), including critical rare earth, Dysprosium. Additionally, it will be assisting to overcome balance problem to substantial extent. On the whole, it has higher basket price. Based on the results of exploration carried out so far, a cumulative resource of more than 1 million tonne has been speculated (Verma 2019b). Accordingly, resource assessment and feasibility studies are required to be done on priority basis on peralkaline granite-hosted REE mineralisation in Siwana ring complex, Barmer district, Rajasthan (Fig. 10.1).

Table 10.2 Price of selected rare earth oxides as on November 08, 2019

S. No.	Oxides	Price range	Average	Unit
1	Lanthanum oxide	12,000–12,500	12,250	RMB/t
2	Cerium oxide	12,000–12,500	12,250	RMB/
3	Praseodymium oxide	340,000–350,000	345,000	RMB/t
4	Neodymium oxide	287,000–290,000	288,500	RMB/t
5	Samarium oxide	12,000–13,000	12,500	RMB/t
6	Europium oxide	210–220	215	RMB/kilogram
7	Gadolinium oxide	157,000–162,000	159,500	RMB/t
8	Terbium oxide	3450–3480	3465	RMB/kilogram
9	Dysprosium oxide	1510–1540	1525	RMB/kilogram
10	Holmium oxide	325,000–330,000	327,500	RMB/t
11	Erbium oxide	160,000–165,000	162,500	RMB/t
12	Thulium oxide	–	–	–
13	Ytterbium oxide	–	–	–
14	lutetium oxide	–	–	–
15	Yttrium oxide	19,500–20,500	20,000	RMB/t

Source Google.com; price.metal.com/Rare-Earth

Conversion rate of Chinese currency, renminbi (RMB): 1 RMB = Rs. 10.20 on November 8, 2019

Note – indicates not available

10.3.5 Other Resources

Follow up prospecting and exploration inputs with focussed REE orientation are needed in areas where favourable geological settings exist/signatures of REE mineralisation have been picked up (Table 10.1). This effort will provide new areas for taking of detailed exploration for REE, that may lead to resource augmentation.

10.3.6 Potential Industrial (Secondary) Resources

Sustained efforts are required to assess feasibility of REE recovery from the available industrial process residues and mine dumps. Initial results, however, appear encouraging. This can be done in close collaboration with all the industrial partners and mining agencies like NALCO, BALCO, HINDALCO, NTPC, UCIL, HZL, KGF, Fertiliser Industry, which produce enormous amount of industrial wastes and mine dumps. In this endeavour apart from REE, other strategic and critical metals may also be recovered. In view of huge availability of industrial wastes and mine dumps, this exercise may prove rewarding in the long run.

10.4 Indian Rare Earth Industry

The IREL (India) Limited (Formerly Indian Rare Earths Limited, IREL), a Government of India Undertaking—Department of Atomic Energy, MINI RATNA—I Company, is involved not only in production of rare earths, but it also produces seven economic heavy beach sand minerals (e.g., ilmenite, rutile, zircon, monazite, leucoxene, sillimanite and garnet; Mohapatra 2019a, b). At present, the rare earth production in India through IREL (India) Limited comes mainly from commercial exploitation of beach placers located in Kerala, Tamil Nadu and Odisha coasts. In addition, Atomic Minerals Directorate for Exploration and Research (AMD), Department of Atomic Energy, Government of India, is also recovering xenotime-bearing polymineral concentrates (7–8 t per year) from stream placers in Jashpur district, Chhattisgarh, central India (Verma 2019a). Stream placer mining yields both heavy and light rare earths, dominated by light rare earths. Processing of monazite by IREL (India) Limited, recovered from beach sand deposits, yields mostly light rare earths, dominated mainly by Ce, La, Nd in decreasing order. Additionally, it also produces value added rare-earth compounds (viz. carbonates of cerium and lanthanum, oxalates of neodymium, praseodymium, yttrium, samarium, gadolinium) and other strategic materials (viz. uranium and thorium salts) from monazite. The products of IREL (India) Limited find applications in diverse industries, namely,

paints and pigments, ceramics, foundries, abrasives, construction, electronics, automobiles, chemicals, metals and alloys, aircraft, satellite launch vehicles, healthcare and nuclear power (www.irel.co.in).

The production of beach sand minerals by IREL (India) Limited was 309,240 t during 2017–18, as against 305,041 t during 2016–17, through its OSCOM (Odisha) and Chavara (Kerala) Units; whereas the Manavalakuruchi Unit (Tamil Nadu) resumed production activities from May 2018 after getting environment clearance (IREL 2018). Significantly, the IREL (India) Limited has planned five ambitious projects (IREL 2018) with distinct objectives. (1) Rare Earth Permanent Magnet. (2) Rare Earth & Titanium Theme Park at Bhopal, Madhya Pradesh. Its purpose is to initiate pilot plants based on laboratory-scale technologies mastered by BARC/other R&D institutes that would share technological know-how to Entrepreneurs and Startups leading to increased production and consumption of rare earths within the country. This may pave the way for setting up value chain in the rare earth sector (IREL 2018). (3) Joint Venture (JV) with Industrial Development Corporation of Odisha Ltd. (IDCOL) and IREL (India) Limited to obtain the Atomic Mineral deposits in the states of Odisha. (4) Capacity Expansion of OSCOM Plant to double the capacity of mineral production of OSCOM Unit of IREL (India) Limited. (5) Titanium Slag Plant to set up 100,000 t per annum titanium slag plant under Build-Own-Operate (BOO) model (IREL 2018).

India also exports its upstream products (rare earth oxides), as IREL (India) Limited has facilities for producing high-quality rare earth oxide. Additionally, IREL (India) Limited signed a sale purchase agreement (SPA) with Toyota Corporation, Japan, and their subsidiary Toyotsu Rare Earth India (TREI) Pvt. Ltd. Visakhapatnam, on 9th December, 2015 (Toyota Tsusho Inks Rare Earths Contract with Indian State Corporation, http://www.toyoto-tsusho.com/english/press/detail/151210_002928.html) for supply of Rare Earth Chloride (RECL) being produced at Monazite Processing Plant (MoPP) at IREL (India) Limited's OSCOM Unit in Odisha to TREI for value addition purposes (IREL 2016; IBM 2018). Supply of 1200 t of RECL on dry metric basis was done by IREL (India) Limited during 2016 to TREI, which IREL (India) Limited intends to increase substantially during the second contract year (IBM 2018). Furthermore, IREL (India) Limited is also involved in separation of individual rare earths at its Rare Earths Division, Aluva Plant, Kerala. Additionally, IREL (India) Limited also entered into memorandum of understanding (MoU) with BARC (which developed technology for manufacturing of RE phosphors), DMRL (which possess technology for production of rare earth magnets) and International Advanced Research Centre for powder metallurgy and new material (ARCI) for development of permanent magnet rings.

10.5 Commercial Demand for REE

The commercial demand for rare earths in India cannot be quantified directly due to the fact that bulk of the rare earth containing products used in various fields are imported from China, Japan and other countries. Thus Indian REE demand has to be adjudged based on the global market trend. Now it is a well-known fact that globally there is a progressively growing commercial demand for REE in various high technology fields. Notwithstanding non-uniform categorisation of REE applications, rare earth market is generally classified into nine domains, e.g., catalysts, polishing, glass, phosphors and pigments, metallurgy, batteries, magnets, ceramics, and others. Out of 119,650 t of estimated global REO consumption in 2015, spread of consumption in various sectors in decreasing order is catalysts (24%), magnets (23%), polishing (12%), other applications (9%), 8% each in metallurgy and batteries, glass (7%), ceramics (6%) and phosphors and pigments (3%) (Zhou et al. 2017). With sustained focus for augmenting preferentially clean energy, e.g., electric vehicles, wind power turbines, energy-efficient lighting, and catalytic converters, global requirement for REE, including in India, would continue to maintain upward growth in coming decades. This situation is going to accentuate more and more challenges for maintaining uninterrupted supply chain of REE. It is going to be more so in light of India's resolve to a target of 170 GW of renewables by 2022, comprising 100 GW of solar energy, 60 GW of wind energy and 10 GW of hydropower. Furthermore, under the National Electric Mobility Mission Plan (NEMMP), the target set by India is 6–7 million units of EVs by 2020; sale of ~0.8 billion LED bulbs by 2019 (Kumar and Bharadwaj 2018). Additionally, renewables will have a 40% share of energy mix by 2030, including goal to have near-complete electrification of surface transport in the coming 15–20 years (Fig. 10.2). Required quantity of LREE and HREE in individual intermediate products and their market share is shown (Fig. 10.3; UNEP 2013; UNCTAD 2014; Kumar and Bharadwaj 2018). The proposed Rare Earth & Titanium Theme Park by IREL (India) Limited may also increase consumption of rare earths by industries within the country.

Individual rare earth elements specific global demand for REO, which is equally applicable for India also, is shown (Fig. 10.4). To cope up with the clean energy growth, projected demand for Nd is going to be doubled to more than 40,000 t of Nd oxide by 2030; followed by Dy and Ce oxides (Fig. 10.4). Current level of requirements for La oxide may remain more or less horizontal, with marginal decrease in growing demand for Y, Eu and Tb oxides. Although requirement of REE in lighting market is anticipated to reduce gradually, the REE demand for wind turbines, electric vehicles and NiMH batteries is likely to keep growing (Zhou et al. 2017). Accordingly, with projected decrease in lighting market in coming years, envisaged criticality of Eu, Tb and Y may not be sustained with reference to their supply (Fig. 10.5; Binnemans et al. 2018), whereas Nd and Dy are likely to become critical, especially Dy, in terms of supply scenario (Fig. 10.5). However, supply of remaining various rare earth oxides required in other industries (Fig. 10.3) may not be adversely affected. Thus maintaining availability of Nd and Dy may pose challenges

Fig. 10.2 Projected Indian REE market for 2020 and 2025 (Modified after Kumar and Bharadwaj, 2018; Based on Ngualla Rare Earth Project)

Fig. 10.3 Required quantity of LREE and HREE in individual intermediate products and their market share (Source google.com, researchgate.net, UNEP 2013; UNCTAD 2014; Kumar and Bharadwaj 2018)

Fig. 10.4 Global demand of REE exclusively for clean energy (after Zhou et al. 2017)

Fig. 10.5 Medium term (2015–2025) criticality matrix showing the five most critical rare-earth elements. Note relatively high supply risk for dysprosium and terbium, compared to neodymium, europium and yttrium (after Binnemans et al. 2018)

to ensure their supply for green energy field alone. Global production data reveals that out of total REE market value, 62.5% is shared by LREE and remaining 37.5% is accounted for by HREE (Zhou et al. 2017).

In Indian scenario, Nd supply can be sustained by processing monazites hosted in beach placers deposits of Odisha, Andhra Pradesh, Tamil Nadu and Kerala (Table 10.1; Fig. 10.1). On an average, monazites from these deposits contain more than 10% Nd oxide (Singh 2020). Furthermore, once commercial mining starts additional supply of Nd can also come from carbonatites of Amba Dongar and Kamthai (Table 10.1; Fig. 10.1), as they contains Nd oxides in the range of 0.13–1.2 wt%. Individual REE minerals hosted in Kamthai carbonatites contain up to >5.0 wt% Nd oxide. Processing of monazites hosted in stream placers of Chhotanagpur Granite Gneiss Complex terrain, central India (Table 10.1; Fig. 10.1), with average 8.8% Nd oxide content, can also supplement Nd supply. The supply for still more scarce and critical rare earth element, Dy, may be regulated through major resources contained in stream placers of central India and upcoming peralkaline granites and associated tuffs of Siwana Ring Complex in Western India (Table 10.1; Fig. 10.1). Xenotimes from Siri stream placers and Kanyaluka contain ~4.5 wt% Dy oxide, whereas peralkaline granites of Rajasthan revealed 0.025–0.05 wt% Dy oxides. Apart from Dy, these resources would take care of supply for remaining individual heavy rare earths needed by other different industries. The LREE and HREE resources required for other products (Fig. 10.3) would continue to come from the existing and future possible REE resources. Needless to say that substantial resources of REE established in India is in the form of monazite contained in heavy mineral sand in coastal beach placers that form a vast resource of LREE (12.47 million tonnes as on March 2017; Mohapatra 2019a, b). This resource may take care of entire LREE requirements of most of the industries (Fig. 10.2 and 10.3). Huge resources of garnet (187 million tonnes; Mohapatra 2019a, b) and zircon (36 million tonnes; Mohapatra 2019a, b) should be assessed for potentiality for low grade REE resources. Together both may also help to some extent to overcome balance problem of individual REE.

10.6 Supply and Demand Chain and Technological Innovation

The Rare Earth Industry has upstream and downstream chain of supply and demand. The first sector comprises exploration, extraction, production of metal oxides, metals and metal alloys, whereas the second one involves manufacturing of intermediate products like permanent magnets and phosphors. Both are integral parts of end-use demand/market, as for example, electric vehicles, acoustic transducer, wind turbines, medical devices and military applications. Although India has proven professional skill both in upstream and downstream domains, but it manifests relatively less in downstream domain of rare earth value chain where expertise appears to be limited to lab-scale in the manufacturing of intermediate products (cf. Kumar and Bharadwaj

2018). Possibly manufacturing of intermediate products is done to the extent to meet only inhouse organisational strategic requirements. Non-availability of intermediate products in open market causes imbalance in downstream sector and builds up price pressure.

As commercial products of existing technologies have not reached to open market, manufacturing of intermediate products require to be accelerated through technological innovation in downstream domain. In this regard, proposed Theme Park of IREL (India) Limited may help to some extent. Also, constant improvements in upstream sectors are needed for progressive growth of closely-knit chain of Indian Rare Earth Industry (cf. Kiggins 2015). This would also help in containing monopoly of China in global rare earth supply chain, for which other major stakeholder countries are also making more stronger their individual indigenous exploration, extraction, processing and manufacturing abilities. Significantly, US and Canada have also recently signed Memorandum of Understanding for critical materials to lessen reliance on China for rare earth supply (REAI News 2020a). Furthermore, it is envisaged that US even plans to hoard rare earth magnets, namely, neodymium magnets, worth tens of millions of dollars (REAI News 2020a). It is going to be more so in light of unavoidable influence of coronavirus on the world's rare earths supply chain (REAI News 2020b).

10.7 Individual REE Balance and Market Price

Due to highly skewed distribution of REE in natural resources, production of individual rare earth by quantity is highly variable leading to huge price variation for each rare earth element (Table 10.2) that keeps on fluctuating constantly in global mineral market. Thus it is also desirable to find additional uses of those individual rare earths whose surplus production cannot be avoided, and also to develop substitutes in domain specific various applications for those rare earths which are scarce or critical in terms of their availability (cf. Binnemans et al. 2018). Other available options for balance problem of rare earths include diversification of REE resources, recycling and reduced use (cf. Binnemans and Jones 2015).

10.8 The Takeaways

The concentration of rare earth element in any geological environment alone does not make it suitable for commercial mining. The ease of exploitation is commonly dictated by favourable geological setting, ore grade, tonnage, existing processing technology, costs and attendant environmental concerns including local people. These aspects need to be assessed properly before commencing exploitation. Apart from strengthening downstream sector, upstream sector also need to be developed for identifying and quantifying additional natural resources to sustain "Rare Earth Industry

Chain”. This endeavour may also involve innovative groups at the interface of information technology and the minerals, metals and materials engineering domains (cf. Pradip et al. 2019). Assessment of effective recovery of REE and associated metals from industrial wastes and mine dumps, comprising ‘Technospheric mining’, should continue to receive focussed attention. The indigenous manufacturing of intermediate products need to be augmented with matching progressive growth of technological advancements. Industrially speaking, promotion of the “Rare Earth Industry” should be an integral part of the present programme of “Make in India” (Singh 2019). In this regard, a beginning can be made by the AMD-IREL-BARC-NFC-DMRL-ARCI combine. To achieve this goal, several of the industrial partners like Aluminium extraction, Thermal Power Plants, Fertiliser Plants, different Mining Agencies and Steel Plants can also be involved as partners. Also, India can promote its ties with countries, as has been established now with Japan for improving its domain knowledge and new technologies for both upstream and downstream processes of the “Indian Rare Earth Industry”. Significantly, according to REAI News (2020a), “2020 looks to be a pivotal year for rare earths”.

References

- Binnemans K, Jones PT (2015) Rare earths and the balance problem. *J. Sustain. Metall.*, vol. 1, pp 29–38.
- Binnemans K, Jones PT, Muller T, Yurramendi L (2018) Rare earths and the balance problem: how to deal with changing markets? *J Sustain Metall* 4:126–146
- Google.com (2019) Top countries for rare earth metal production. <https://investingnews.com>critical-metals-investing>rare-earth-investing>, May 2019. Visited on 8.10.2019
- IBM (2018) Indian minerals year book 2017 (Part-III: Mineral reviews), 56th Edition, Rare earths. March 2018, Ministry of Mines, Government of India, Nagpur, pp 24–1 to 24-7
- IREL (2016) Indian Rare Earths Limited, March 2016. <http://www.irel.gov.in/scripts/unit.asp>
- IREL (2018) 68th annual report of the Indian Rare Earths Limited for the year 2017–18. Indian Rare Earths Limited, pp 1–180. www.irel.co.in
- Kiggins RD (2015) The political economy of rare earth elements: rising powers and technological change. Palgrave Macmillan, United Kingdom
- Kumar P, Bharadwaj MD (2018) Indian rare-earth industry: need and opportunity for revival and growth. <https://www.researchgate.net/publication/323656626>
- Mohapatra AK (2019a) Mining and mineral beneficiation operations of beach sand minerals in India. In: Proceedings of National seminar on strategic mineral exploration for sustainable development: emerging trends and challenges. Organised by Atomic Minerals Directorate for Exploration and Research, Southern Region, Bengaluru, May 7–8, 2019, Abstract Volume, pp 63–64
- Mohapatra AK (2019b) Mining and mineral beneficiation operations of beach sand minerals in India. In: Proceedings of Symposium on Science, Technology and Applications of Rare Earths (STAR-2019), Organised by Rare Earth Association of India (REAI), Dec 5–7, 2019, Mumbai, Abstract Volume, pp 15–16
- Ngualla Rare Earth Project Report (2016) <http://www.peakresources.com.au/IRM/company/showpage.aspx/PDFs/2953-95508946/NguallaRareEarthProject>. Update March 2016
- Pradip, Gautham BP, Reddy S, Runkana V (2019) Future of mining, mineral processing and metal extraction. *Trans Indian Inst Met* 72(8):2159–2177. <https://doi.org/10.1007/s12666-019-01790-1>
- Rare Earth Association of India (REAI) (2020a). “2020 looks to be a pivotal year for rare earths”. In: Collected, compiled and edited by Raj Nair, REAI, News, vol. 20, No. 1, January 2020, India, pp 1–78.

- Rare Earths Association of India (REAI) (2020b) “The inevitable impact of the coronavirus on the world’s rare earths supply”. In: Collected, compiled and edited by Raj Nair, REAI, News, vol 20, No. 3, March 2020, India, pp 1–22
- Singh Y (2019) Rare earth elements: Indian resource scenario. Proceedings of Symposium on Science, Technology and Applications of Rare Earths (STAR-2019), Organised by Rare Earth Association of India (REAI), December 5–7, 2019, Mumbai, Abstract Volume, pp 52–53
- Singh Y (2020) Rare earth element geochemistry of monazites from beach sand deposits of Indian coasts: implication for clean energy. *J Appl Geochem* (in press)
- Toyota Tsusho Inks Rare Earths Contract with Indian State Corporation. http://www.toyoto-tsusho.com/english/press/detail/151210_002928.html
- United Nations Conference on Trade and Development (UNCTAD) (2014) *Commodities at a glance* (No. 5), New York & Geneva
- United Nations Environment Programme (UNEP) (2013) *Metal recycling: opportunities, limits, infrastructure*. A report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter MA, Hudson C, Van Schaik A, Heiskanen K, Meskers C, Hagelueken C
- Verma MB (2019a) Seven decades of atomic mineral exploration in India. In: Proceedings of national seminar on strategic mineral exploration for sustainable development: emerging trends and challenges. Organised by Atomic Minerals Directorate for Exploration and Research, Southern Region, Bengaluru, May 7–8, 2019, pp 1–3
- Verma MB (2019b) Rare earth element (REE) resources of India in world’s perspective. In: Proceedings of symposium on science, technology and applications of rare earths (STAR-2019), Organised by Rare Earth Association of India (REAI), Dec 5–7, 2019, Mumbai, Abstract Volume, pp 11–12
- Zangeneh S (2018) State of India’s rare earth industry—understanding India’s current position. *International Strategic and Security Studies Programme (ISSSP) Reflections* No. 57, Nov 28, 2018
- Zhou B, Li Z, Chen (2017) Global potential of rare earth resources and rare earth demand from clean technologies. *Minerals* 7, p 203. <https://doi.org/10.3390/min7110203>