J. Earth Syst. Sci. (2020)129 165
https://doi.org/10.1007/s12040-020-01447-4

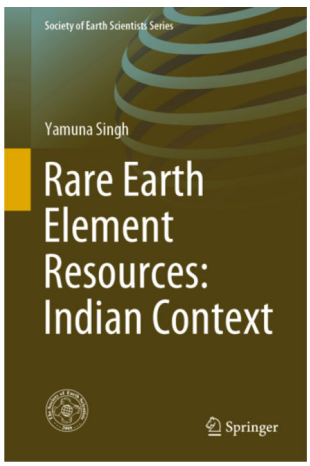
BOOK REVIEW

Rare earth element resources: Indian context

YAMUNA SINGH
Springer & The Society of Earth Scientists Series, ISBN 978-3-030-41353-8

Reviewed by N V CHALAPATHI RAO

Centre of Advanced Study in Geology, Institute of Science, Banaras Hindu University, Varanasi 221 005, India. e-mail: nvcrao@bhu.ac.in



We are living in times wherein there is an ever increasing demand for rare earth elements (REEs), which are ruling the contemporary mineral market owing to their applications in electronics, catalysts, magnets, metallurgy, batteries, glass, ceramics, pigments, phosphors, polishing, besides many other utilities. The REE mineral resources, thus, undoubtedly have emerged as those having strategic importance. Given the uncertainty in their supply to the world market, due to denial of REE material by countries such as China, exploration efforts have been intensified world-wide to identify REE resources in various geological milieu.

Published online: 23 July 2020

Even though exploration for REE in India began in the 1950s and several REE resources in various geological settings have been identified since then, India's status as a major player in the international RE industry remains insignificant. Against this backdrop, Yamuna Singh, who served as a scientific officer for 36 years exploring atomic minerals and REE in the Atomic Minerals Directorate for Exploration and Research (AMD) – an organization under Department of Atomic Energy (DAE) – came up with a timely compilation on the rare earth element resources in Indian context. The book, with a foreword by the eminent geoscientist T M Mahadevan runs into 395 pages and narrated in ten chapters with scores of illustrations and data sets. Chapter-1 is an 'Introduction' which provides an overview of rare earth elements, their place in the periodic table, discovery, applications, list of selected rare earth minerals, their crustal abundances, world REE resources and major classifications in vogue of REE deposits. We are told that despite the presence of hundreds of REE-bearing minerals, only three (bastnaesite, monazite for light REE, and xenotime for heavy REE) are important. Australia, China, Brazil, and Vietnam account for the bulk of the world's REE reserves as well as in production. Based on their genetic links with igneous, sedimentary and secondary formation, the global REE deposits are conventionally classified into following broad groups: (i) carbonatites, (ii) agpaitic nepheline

syenites and peralkaline–alkaline felsic rocks, (iii) hydrothermal veins and pegmatites, (iv) quartz–pebble conglomerate, (v) stream and beach placers, (vi) residual/supergene weathering, (vii) ion adsorption on clays, (viii) iron oxide–copper–gold type, and (ix) other types (including industrial wastes). Even though the Indian REE resources fit in this classification, the author chose to describe them in the order of their commercial importance.

With ∼6000 km of coastal length, India has the world's richest shoreline heavy mineral placer deposits (dominated by ilmenite, rutile, sillimanite, and zircon) which also include REE bearing minerals such as monazite, xenotime, and garnet. Chapter-2 on 'Beach sand deposits' deals with world coastal placer deposits, Indian coastal placer deposits, segment-wise distribution, range and the average grade of total heavy minerals, geochemistry of REE minerals, and also provides with their mining and beneficiation scenarios. Chatrapur (Odisha), Manavalakurichi, Midalam, Vayakallur (Tamil Nadu), and Chavara (Kerala) constitute some of the major REE deposits.

Chapter-3 is devoted to 'Inland stream placers' wherein clastic accumulation of REE minerals takes place in alluvial or colluvial deposits referring to fluvial placers/soil accumulations in the areas of Precambrian shields. Most important riverine REE placers in the country is located at the Chhotanagpur Gneissic Terrain in eastern India, and the Godhra Granite in western India. Other occurrences are located in the Bastar cratonic terrain (along Jhiram, Jamair, Dumam, Mari Kawra, Nakti, and Dussanada rivers), Dharwar craton (Dharmavaram and Pathapalem streams in Telangana, granitic soils of Hassan, Mandya and Raichur districts of Karnataka), Southern Granulite Terrain (Goddaru Vanka stream and granitic soils in Kullampati area in North Arcot district and Salem district, respectively), and northeast India (Kameng river and Garo hills). The author opines that younger potassic granites, alkali granites, and associated soils and quartz veins in the Dharwar craton hold much promise for future REE exploration.

Rare earth elements, along with Nb, Th, U, P and Sr, are capable of readily partitioning into carbonatitic melts and more than 50% global REE resources are accounted for by carbonatites. However, only a few of them such as Mountain Pass (California, USA), Mount Weld (Australia) and Maoniuping (China) attains high degree of REE concentrations to make them economically viable. Chapter-4 is concerned with the Indian carbonatites and their REE scenario. The age of the Indian carbonatites ranges from Archaean (Hogenakal in the Southern Granulite Terrain) to end-Cretaceous (Amba Dongar, NW India) and majority of them are associated with the rift systems. Amba Dongar and Kamthai (both in NW India) contain the bulk of the REE resources and contain bastnaesite as the main REE hosting phase. The carbonatites of southern India (Pakkanadu, Samalpatti, Mulakkadu, etc.) are, on the other hand, dominated by monazite. Not much beneficiation work has been carried out on the Indian carbonatites apart from those at Sevattur, Samchampi, and Sung Valley (NE India) and their REE potentiality need to be ascertained.

Peralkaline–alkaline felsic rocks ('A' type and 'within-plate' granite, rhyolite, and syenite) represent highly fractionated and volatile-rich igneous rocks. High Na, Cl, and F contents of peralkaline melt facilitates the formation of complex REE minerals often at the expense of zircon and ilmenite. Such rocks occurring in Kola peninsula (Russia), Niger-Nigeria, Gardar Province (Greenland), Rapakivi Granites (Finland), and Pan-African Arabian shield are known to host significant REE and other rare metals world-wide and are generally confined to anorogenic tectonic setting linked to rifting. Chapter-5 provides a synthesis on the REE concentrations in Indian peralkaline rocks and their geological distribution. Peralkaline rocks associated with the Siwana ring structure (Rajasthan), Alech Hills and Sudasana (Gujarat), Kinwat (Maharashtra) and a 300 km N–S trending belt of granitoids (including the Kanigiri granite, Vinukonda granite, Darsi granite, and Podile granite) towards the east of the Cuddapah basin are shown to contain substantial REE resources.

Hydrothermal processes, involving interaction of heated aqueous solutions with intervening rocks, under appropriate conditions are known to result in REE deposits (in particular, light REE) hosted by veins and stock-works as at Bayan Obo (China), Buffalo Mine (South Africa), Gallinas Mountains (USA), Karonge (Burundi), and Olympic Dam (Australia). Chapter-6 concerns REE mineralization associated with hydrothermal veins in diverse geological environments of India. Such veins occurring in the Singhbhum shear zone, South Purulia shear zone, charnockites of Visakhapatnam area and 320 km long albitite belt and Gogi

uranium prospect (Bhima basin) are shown to contain substantial REE to merit them to be considered as resources.

Of the three different types of pegmatites, viz., homogeneous, zoned, and layered, the zoned felsic varieties (such as those from Madagascar) are known to be the source of economically valuable rare metal and REE deposits. The Indian pegmatites are yet to be qualified as an REE deposit since only a few of them are endowed with high concentrations of REE minerals. However, they may be recovered as a by-product of mining for other economic minerals such as beryl, mica, columbite–tantalite, uraninite, etc. Chapter-7 outlines distribution and REE potential of pegmatites from various cratonic domains of India and reveal that monazite, allanite, chevkinite, and xenotime constitute major REE phases.

Chapter-8 addresses several potential natural REE resources including (i) quartz pebble conglomerate, (ii) iron oxide breccia complex, (iii) phosphorites and phosphatic sediments, (iv) bauxite, (v) laterite, (vi) sea floor muds, and (vii) ion adsorption clays, etc., which are globally known to constitute REE resources albeit selectively. Even though not much data is available from the Indian context, the initial studies appear encouraging. Chapters 9 and 10 are concerned with potential industrial (secondary) resources and evaluation of the commercial potential of the Indian REE occurrences. Non-conventional resources such as photo gypsum, phosphoric acid, coal fly ash, red mud (bauxite residue), mine tailings, metallurgical slags, electrical and electronic wastes are suggested to be investigated for the recovery of REE. Likewise, beach sands and carbonatites are prioritized as most promising deposits for light REE whilst inland stream placers are envisaged to be good resources for heavy REE.

To me, following are some of the most important aspects which appeal the most about this compilation: (i) bringing together at one place scattered information in various journals, memoirs, technical reports and those in not so easily accessible various institutional publications; (ii) approaching each chapter from a combined mineralogical, geochemical, exploration and beneficiation view point aided with geological maps, wherever available; (iii) even though the focus is on the Indian context, there are a number of examples and references drawn from the world over which provide a comprehensive outlook to the reader; (iv) commercial potential and prioritization of Indian REE deposits and bringing forth potential industrial (secondary) resources to look forward in the future, and (v) a plethora of up-to-date bibliography at the end of each chapter provide ample opportunities to prospective reader/researcher to fruitfully get back to the original sources. The lack of an appendix at the end of the book listing keywords and their respective page number is perhaps the only drawback which I can point out in this book. In summary, this publication is a useful and thought-provoking contribution on the REE resources from the Indian shield and merits a place in earth science departmental libraries as well as in the curriculum of post-graduate economic geology/mineral resources courses being taught in Indian universities.