



A comparison of global rare earth element (REE) resources and their mineralogy with REE prospects in Sri Lanka

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ABSTRACT

Rare earth elements (REEs), a group of 17 elements comprises 15 lanthanides, scandium and yttrium, are largely attracting the world's attention due to their importance in a wide variety of advanced technological applications. Global REEs production is mainly sourced from resources, such as carbonatites, alkaline igneous rocks, placers, laterites, and ion-adsorption clays. Recently, REE demand has been escalating, especially due to the REE applications in renewable energy and defense sectors, expecting a worldwide shortage of REE supply in the future. Therefore, REEs have been widely accepted as strategic elements in the world, which compels to prospect for new and alternative REE resources. In this context, Sri Lanka has a favorable geological setting which implies the presence of REE mineralization. Previous geochemical studies in Sri Lanka have reported significant concentrations of REEs in different geological formations and mineral resources. Accordingly, Pulmoddai and other beach placer deposits, Eppawala carbonatite, alluvial placer deposits, and pegmatites have been identified as potential REE resources in Sri Lanka. Monazite, apatite, allanite, and zircon are the primary rare earth (RE) minerals found in the preceding resources. The Pulmoddai mineral sand deposit is considered as the most potential REE resource in the island, which is enriched in monazite containing more than 61% of light rare earth elements (LREEs). Similarly, Eppawala carbonatite contains high concentrations of LREEs. However, despite their significant REE enrichments, to date, no attempt has been made to recover these REE prospects, which essentially conceals their potential of catering for both local and global REE supply chains.

1. Introduction

In 1787, a unique black mineral was found in a small quarry in Sweden containing a series of new kinds of elements, lately named as rare earth elements (REEs). It was the world's first ever discovery of REEs and cerium (Ce) was the first rare earth element (REE) isolated in 1803 (Pecharsky and Gschneidner Jr, 1999). Since then, more than 250 rare earth (RE) minerals have been identified in different geological formations and mineral resources, worldwide. REEs are a set of seventeen chemical elements comprising 15 lanthanides, yttrium (Y) and scandium (Sc) (Balaram, 2019). REEs are typically divided into two sub-groups, namely light rare earth elements (LREEs) from lanthanum (La) to samarium (Sm) and heavy rare earth elements (HREEs) from europium (Eu) to lutetium (Lu) plus Y. However, Sc does not belong to any of these categories, as it does not occur in the same deposits as the other REEs (Van Gosen et al., 2014).

REEs are not as rare as their name suggests. They are lithophile elements (elements enriched in the earth's crust), which have a total crustal abundance of 220 ppm (Table 1), even higher than that of carbon (200 ppm). Moreover, some REEs are more abundant than most of the frequently used industrial metals, such as copper (Cu), cobalt (Co), lead (Pb), and tin (Sn) (Gupta and Krishnamurthy, 2005). According to Table 1, La, Ce, Y, and neodymium (Nd) are the most abundant REEs in the earth's crust, whereas promethium (Pr) is the rarest of all REEs. Nevertheless, the commercial availability and their metallurgical usage do not depend on its crustal abundance. They depend on factors, such as (1) the degree of natural enrichment of a metal into the ore deposit (2) the relative feasibility of separating the ore from the host rock, and (3) the feasibility of extracting the metal from the ore. Since REEs do not satisfy the aforementioned requirements, they are termed as "rare" (Hampel and Kolodney, 1961).

REEs exhibit unique chemical, physical, magnetic, and luminescent

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Table 1
Abundance of REEs in the Earth's crust (ppm).

Elements	Mason and Moore (1982)	Jackson and Christiansen (1993)	Sabot and Maestro (1995)	McGill (1997)	Lide (1997)	Kumari et al. (2015)
Sc	–	–	10	5–10	22	ng
Y	33	29	28	28–70	33	ng
La	30	29	18	5–18	39	30.0
Ce	60	70	46	20–46	66.5	60.0
Pr	8.2	9	5.5	3.5–5.5	9.2	6.7
Nd	28	37	24	12–24	41.5	27.0
Sm	6	8	6.5	4.5–7	7.05	5.3
Eu	1.2	1.3	0.5	0.14–1.1	2	1.3
Gd	5.4	8	6.4	4.5–6.4	6.2	4.0
Tb	0.9	2.5	0.9	0.7–1	1.2	0.7
Dy	3	5	5	4.5–7.5	5.2	3.8
Ho	1.2	1.7	1.2	0.7–1.2	1.3	0.8
Er	2.8	3.3	4	2.5–6.5	3.5	2.1
Tm	0.5	0.27	0.4	0.2–1	0.52	0.3
Yb	3.4	0.33	2.7	2.7–8	3.2	2.0
Lu	0.5	0.8	0.8	0.8–1.7	0.8	0.4

*ng = not given.

properties, due to their different atomic structures and states (Zepf, 2013; Dushyantha et al., 2020). These properties promote a multitude of technological advantages, such as low energy consumption, high efficiency, miniaturization, speed, durability, and thermal stability. Therefore, REEs are commonly used in modern high technological applications, such as rechargeable batteries, autocatalytic converters, super magnets, LED lighting, fluorescent materials, and solar panels (Balaram, 2019). This immense consumption of REEs in the advancement of modern high-tech and green technologies has resulted in a rapid growth in the REE demand over the last two decades (Mancheri et al., 2019). Moreover, it has been predicted that the demand for REEs could increase by 7–8% annually (Kingsnorth, 2016). Since global production is presented in terms of rare earth oxides (REOs), global production estimation of REOs has increased approximately from 100 to 200 thousand metric tonnes over the period of 2010–2018, and it is forecasted to increase over 250 thousand tonnes by the year 2025 (Fig. 1).

Based on the estimations in 2019, China holds over 79% of the world's mined production and 37% of the world's REE reserves (Terry, 2019). Such a high share of the supply can be risky, since it creates a

Table 2
Primary RE minerals and their formulae ().
Source: Dostal, 2017

RE Minerals	Formula
Allanite	(Y, Ln, Ca) ₂ (Al, Fe ³⁺) ₃ (SiO ₄) ₃ (OH)
Apatite	(Ca, Ln) ₅ (PO ₄) ₃ (F, Cl, OH)
Bastnaesite	(Ln, Y) (CO ₃)F
Eudialyte	Na ₄ (Ca, Ln) ₂ (Fe ²⁺ , Mn ²⁺ , Y)ZrSi ₈ O ₂₂ (OH, Cl) ₂
Fergusonite	(Ln, Y)NbO ₄
Gittinsite	CaZrSi ₂ O ₇
Limoriite	Y ₂ (SiO ₄)(CO ₃)
Kainosite	Ca ₂ (Y, Ln) ₂ Si ₄ O ₁₂ (CO ₃).H ₂ O
Loparite	(Ln, Na, Ca)(Ti, Nb)O ₃
Monazite	(Ln, Th)PO ₄
Mosandrite	(Na, Ca) ₃ Ca ₃ Ln (Ti, Nb, Zr)(Si ₂ O ₇) ₂ (O, OH, F) ₄
Parisite	Ca(Ln) ₂ (CO ₃) ₃ F ₂
Pyrochlore	(Ca, Na, Ln) ₂ Nb ₂ O ₆ (OH, F)
Rinkite (Rinkolite)	(Ca, Ln) ₄ Na(Na, Ca) ₂ Ti(Si ₂ O ₇) ₂ (O, F) ₂
Steenstrupine	Na ₄ Ln ₆ Mn ₂ Fe ₂ (Zr, Th)(Si ₆ O ₁₈) ₂ (PO ₄) ₇ ·3H ₂ O
Synchysite	Ca(Ln)(CO ₃) ₂ F
Xenotime	YPO ₄
Zircon	(Zr, Ln)SiO ₄
Davidite	(Ce, La)(Y, U)(Ti, Fe ⁺³) ₂ 20O ₃₈

monopoly in REE industry. China, for example, restricted REE exports to Japan over a territorial rivalry, in 2010 and it triggered an increase of REE prices and panic buying. However, lately in 2010, China removed the supply restriction imposed on Japan and lowered their REE export quotas. Due to China's monopoly and the escalating demand of REEs, it has been forecasted that a significant supply risk for REEs may arise in the near future. Therefore, REEs have been considered as the critical elements, especially HREEs, such as dysprosium (Dy), terbium (Tb), and Y (Balaram, 2019).

Secondary REE resources, such as e-waste, phosphogypsum, and mine tailings have become promising sources; however, their contribution to cater the ever-increasing REE demand is not sufficient. Therefore, natural REE resources are continued as the major source of REEs (Binnemans et al., 2013). REEs in natural RE resources do not exist as individual metals due to their high reactivity, and thus, they are found in various minerals. Among all the RE minerals that are identified to date, only a few minerals, such as bastnaesite, monazite, and xenotime (Table 2) are commercially used to produce REEs (Dostal, 2017).

Currently, bastnaesite is considered as the primary mineral of the world's REE production since it is abundantly found in the world's

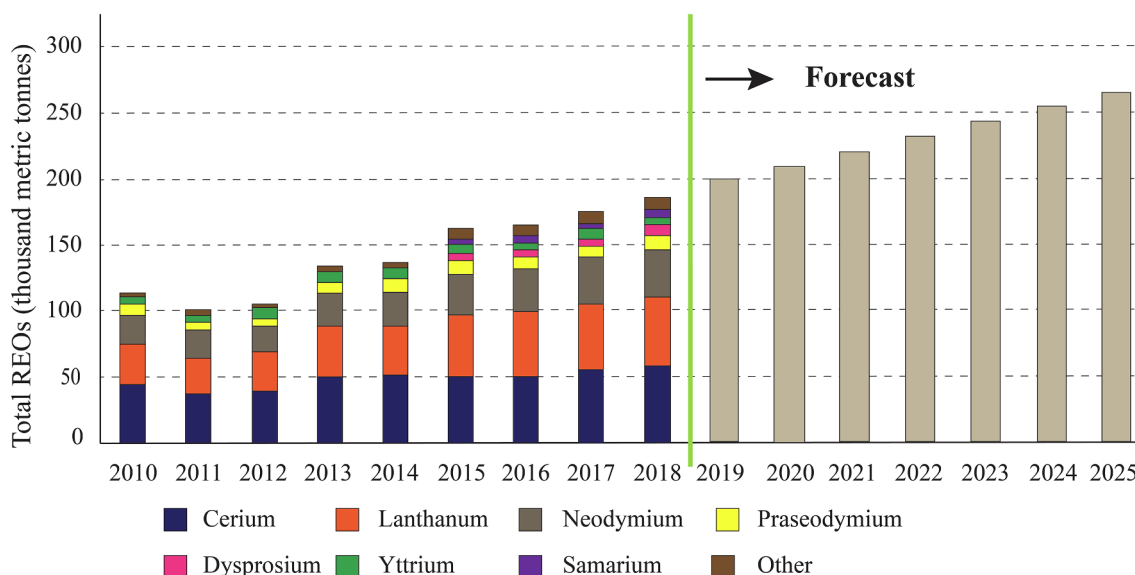


Fig. 1. Total REOs production estimates (2010–2018) and forecasts (2019–2025) (Source: Terry, 2019).

largest RE mines: Bayan Obo in China and the Mountain Pass deposit in the USA. Bastnaesite contains approximately 75% of REOs and considered as the primary source of LREEs. Bastnaesite mainly occurs in vein deposits, contact metamorphic zones, and pegmatites, whereas carbonate – silicate rocks with alkaline intrusive, quartz veins, fluorite-bearing veins, and breccia fillings in Permian sandstone are also found to be the host rocks of this mineral (Gupta and Krishnamurthy, 2005; Jordens et al., 2013; Voncken, 2016). Monazite is widely distributed in the world, occurring in different geological environments and mineral deposits. It contains approximately 70% of REOs comprising 10–40% La₂O₃, 4–12% ThO₂, 20–30% Ce₂O₃, and high amounts of Nd, Pr, and Sm (Thompson et al., 2012). Although monazite is considered as a major source of LREEs, their extraction has become a difficult process due to the high enrichment of radioactive elements, such as thorium (Th) and uranium (U) (Voncken, 2016; Xaba et al., 2018). Monazite mainly occurs in beach placer deposits, usually in high concentrations, while it is also found as an accessory mineral in granite, gneiss, and other igneous and metamorphic rocks (Wall, 2014). According to the estimations in 2005, about 10.21 million tonnes of terrestrial monazite placer deposits were found in the world, and those are distributed among China, USA, and India in percentages of 36%, 13%, and 3%, respectively (Pandey, 2011). In addition, other key RE minerals are listed Table 2.

In recent years, a necessity of exploration for new and alternative sources of REEs was emerged due to the supply risk of REEs and consequently, many new deposits have now been discovered (e.g. Bokan-Dotson and Bear Lodge in the USA, Hoidas Lake in Canada, Norra Karr in Sweden) (McLemore, 2015; Balaram, 2019). In this context, Sri Lanka has a geological setting that is favourable for REE resources. Previous geochemical studies in Sri Lanka disclose clear evidence of significant concentrations of REEs in different geological environments and resources. Therefore, this paper provides a critical overview on potential REE resources of Sri Lanka from a geological point of view. Their mode of occurrence is discussed in detail, including comparisons to the known types of REE resources in the world. This comparison will be useful to understand the significance of Sri Lankan REE resources and develop future exploration studies to appraise the economic viability.

2. REE resources and their global distribution

REE resources are located where REEs are concentrated significantly above the average crustal abundance through geological processes, namely, primary processes (i.e. magmatic and hydrothermal) and secondary processes (i.e. weathering and erosion) (Goodenough et al., 2016). The major known types of REE deposits disseminated across the world are carbonatites, alkaline igneous rocks, pegmatites, iron oxide copper–gold (IOCG) deposits, vein and skarn deposits, placers, laterites, ion adsorption clays, and offshore sources. Currently, about 851 REE deposits have been identified in the world, which are mainly distributed in countries, such as China, USA, Brazil, Russia, and Australia (Orris and Grauch, 2002; Zhou, 2017a).

2.1. Types of REE resources

REE resources are categorized into different classifications based on their geological associations. These classifications are helpful in prospecting new deposits and to determine their feasibility of mining, processing, and refining (Weng et al., 2015). Most frequently used classification is based on the mode of origin, which divides all the REE deposits as primary and secondary deposits. Primary RE deposits are the formations associated with metamorphic rocks, pegmatite, carbonatite, and hydrothermal veins, enriched by primary processes (magmatic and hydrothermal). In contrast, secondary deposits, namely, placers, laterites, bauxite, and ion-adsorption clays, are formed by weathering and erosion of the primary sources (Balaram, 2019).

2.1.1. Carbonatites

Carbonatites are carbonate-rich igneous rocks formed by the solidification of deep-seated magma that intruded into the earth's crust. Majority of carbonatites occur in association with concurrent ultramafic and alkaline silicate rocks as flows, plugs, dykes, cone sheets, and sills. There are more than 500 known occurrences of carbonatites throughout the world except in Antarctica and two oceanic localities (Woolley and Kjarsgaard, 2004). Mountain Pass in California, Kangankunde Hill in Malawi, Gallinas Mountains in New Mexico, Bayan Obo and Mao-niuping in China and Magnet Cove in Arkansas are well-known REE-bearing carbonatite deposits in the world. Among these, Bayan Obo in China is considered as the biggest REE deposit in the world (Long et al., 2012).

Carbonatites comprise more than 50% magmatic carbonate minerals, such as calcite and dolomite, along with less than 20% SiO₂ (Chakhmouradian and Zaitsev, 2012). Bastnaesite, apatite, monazite, allanite, parisite, and synchysite (Table 2) are the most common REE-bearing minerals found in carbonatites, whereas bastnaesite is considered as the primary RE mineral in carbonatite deposits. REE enrichment in carbonatites (generally in the range of 250–8000 ppm) is comparatively higher than the same in igneous rocks. However, LREEs are relatively more abundant in carbonatites than HREEs (Smith et al., 2015).

2.1.2. Alkaline igneous rocks

Alkaline igneous rocks is a major type of REE resources in the world, which consists of REE-enriched intrusions. Generally, these intrusions have both magmatic and hydrothermal origins. However, the most significant REE enrichments are observed when the deposits are associated with both alkaline and peralkaline intrusions (Dostal, 2017). Despite being undersaturated (nepheline syenite) or oversaturated (peralkaline granites), these intrusions comprise a variety of unusual sodic minerals, such as feldspathoids, sodic amphiboles, and sodic pyroxenes. Many REE-enriched alkaline igneous rocks are found worldwide and those are currently in the production (e.g. Lovozero and Khibiny in the Kola Peninsula, Russia), development, or exploration stages (e.g. Thor Lake in Canada, Ilímaussaq in Greenland, Strange Lake Complex in Canada, and Toongi in Australia) (Marks et al., 2011). Ilímaussaq and Motzfeldt in Greenland, Norra Ka`rr in Sweden and Red Wine and Kipawa in Canada are well-known agpaitic nepheline syenite complexes, in which eudialyte (Table 2) is considered as their main ore mineral. However, loparite (Table 2) is found to be the major RE mineral in the Lovozero deposit in Russia (Sørensen, 1992; Mariano and Mariano, 2012; Goodenough et al., 2016; Dostal, 2017). Although agpaitic nepheline syenite deposits are larger in size, they have relatively low total RE oxide (TREO) grades (generally ≤ 1 wt%). They typically show a flatter REE distribution pattern compared to carbonatites and have a negative Eu anomaly. Therefore, in the process of producing 1 kg of Nd, a considerable content of Dy will also be produced with lesser amounts of La and Ce (Machacek and Kalvig, 2016). Moreover, this type of deposits contains small amounts of U and Th, which is more advantageous considering sustainable mine development (Goodenough et al., 2016).

Peralkaline granites are another type of alkaline igneous rocks being actively explored for REEs. These granites have been altered by late-stage magmatic and hydrothermal activities. Strange Lake in Canada, Khaldzan-Buregtey in Mongolia, and Bokan Mountain in Alaska are a few examples of this type of deposits (Salvi and Williams-Jones, 2006; Dostal, 2017). Similarly, alkaline syenitic complexes and felsic volcanic suites with REE-enriched mineralization, such as Thor Lake (Nechalacho) in Canada and Ditrău in Romania are affected by the late-stage hydrothermal activities (Sheard et al., 2012; Timofeev and Williams-Jones, 2015; Goodenough et al., 2016). Alkaline syenitic type of deposits also indicates a relatively flattened REE distribution pattern with a strong negative Eu anomaly. The mineralogy of these deposits varies with REE-bearing silicates and phosphates, such as allanite, zircon,

monazite, and xenotime (Table 2) as well as REE carbonates and oxides. However, this complexity of mineralogy in alkaline igneous rocks results in significant challenges in the processing of ore minerals (Jowitt et al., 2017).

2.1.3. Pegmatites

Granitic pegmatites are coarse-grained igneous rocks with an overall granitic composition. These pegmatites are formed by the cooling of granitic magma that derived from re-melting of crustal materials. Pegmatites are generally in the form of dykes, lenses or veins, and mostly found in cratons and metamorphic belts, surrounding areas of large granitic bodies, contact zones of granite, and skarns associated with granite (Jackson and Christiansen, 1993). These deposits are mainly classified into four classes, namely abyssal, muscovite, rare-element, and miarolitic on the basis of the metamorphic environment of their host rocks, mineralogy, elemental composition, and texture (Černý et al., 2012). The Platt mine in Wyoming, USA was the only industrially mined pegmatite deposit for REE production. However, Cooglegong-Pinga Creek in Western Australia was mined on a small scale (Jaireth et al., 2014). Strange Lake Complex in Quebec-Labrador, Canada is also a highly REE enriched deposit, and it is a peralkaline A-type granitic pluton hosted by hydrothermally altered pegmatites and adjacent granites (Siegel et al., 2018).

Within the pegmatite classes, the rare-element class pegmatites are highly enriched in REEs compared to other classes (Ginsburg et al., 1979). Rare-element pegmatites are subdivided into three families, namely, LCT, NYF and mixed, based on their bulk composition, typical assemblages of trace elements, and types of granites associated with them. LCT pegmatites are enriched in lithium (Li), caesium (Cs), and tantalum (Ta), while NYF pegmatites are enriched in niobium (Nb), Y, and fluorine (F). However, the mixed family is composed of combined characteristics of LCT and NYF families (Černý and Ercit, 2005). In addition to major minerals, such as quartz, K-feldspar, albite, and muscovite, LCT pegmatites contain RE minerals as well (Bradley and McCauley, 2013). NYF pegmatites contain high amounts of zircon, fergusonite-(Y), columbite-(Fe), allanite-(Ce), xenotime-(Y), monazite-(Ce, Nd), thorite, and gummite (Mahmoud, 2019). The mixed type pegmatites include various Y, REE minerals, such as (Nb, Ta, Ti) oxides and silicates (Novák et al., 2012).

Most of the pegmatites consist of about 65% feldspar, 25% quartz, 5–10% mica, and 5% of other accessory minerals, such as garnet, tourmaline, and spodumene (Glover et al., 2012). Granitic pegmatites contain many industrially significant elements, such as Li, rubidium (Rb), Cs, beryllium (Be), gallium (Ga), Sn, Nb, Ta, U, Th, zirconium (Zr), hafnium (Hf), and REEs. NYF pegmatites have higher REE concentrations compared to LCT pegmatites. Due to high REE concentrations and extraction potential for various industrial minerals, such as quartz, feldspar and mica, granitic pegmatite is identified as an effective resource for REEs in an economic point of view (Černý, 1991).

2.1.4. Iron oxide copper–gold (IOCG) deposits

Iron oxide copper–gold (IOCG) deposits are the largest source for U, the third largest for Cu and an important source of Au. IOCG deposits also contain REEs in economic concentrations, and therefore, they are considered as a significant REE resource in the world. However, only a few studies have been carried out for REE mineralization in IOCG deposits and as a result, IOCG deposits are being highly debated in regard of the origin of REEs and REE mobilization. According to Groves et al. (2010), REE mineralization in IOCG deposits is derived from a metal-rich, metasomatized sub continental lithospheric mantle. In contrast, some studies have suggested that REEs are originated from either crustal sources, such as felsic magmas, felsic intrusions/volcanic rocks, and sedimentary rocks or from magmatic/non-magmatic REE-carrying fluids (e.g. Skirrow et al., 2007; Chen and Zhou, 2015). Generally, REE mobilization in the IOCG deposits occurs in the later Cu-mineralizing stage. Due to abundant fluorite and REE-bearing fluorocarbonate

occurrences in IOCG deposits, for many years, researchers assumed that REE-fluoride complexes facilitate the hydrothermal REE transport (e.g. Oreskes and Einaudi, 1990; Williams-Jones, 2015). However, recent modelling with experimental data indicated that fluoride ions promote depositions of RE minerals, such as monazite, apatite, and allanite by acting as binding ligands, rather than being carriers in REE mobilization (Williams-Jones et al., 2012; Migdisov and Williams-Jones, 2014; Li and Zhou, 2018).

There are eleven provinces of identified IOCG deposits worldwide including (1) Gawler Craton, South Australia (Hayward et al., 2010), (2) Carajás mineral province, Brazil (Xavier et al., 2010), (3) Mount Isa Inlier, Northern Australia (Duncan et al., 2014), (4) Central Andean Coastal Belt, Southern Peru and Northern Chile (Chen et al., 2010), (5) Kangdian Copper Belt, Southwest China and Northern Vietnam (Zhao and Zhou, 2011), (6) Khetri Copper Belt, India (Knight, 2002), (7) Lufilian Arc, Zambia (Wilhelm, 2008), (8) Great Bear Magmatic Zone, Canada (Corriveau et al., 2010), (9) Southeast Missouri Iron Province, USA (Seeger and Porter, 2000), (10) Fennoscandian Shield, North Finland (Billström et al., 2011), and (11) West African Craton, Mauritania (Kolb et al., 2010). The most deposits in these provinces contain REEs in economic concentrations.

IOCG deposits consist of a diversified mineralogy, including minerals of iron oxide, sulphide, silicate, carbonate, and phosphate phases. Generally, iron oxide minerals are the major ore minerals found in IOCG deposits and other minor or accessory minerals present in concentrations in the range of 1–5% (Williams et al., 2005). REE mineralogy in IOCG complexes differs based on the host rock. For example, in magnetite-dominated ores, REEs are commonly enriched in rock forming minerals, such as apatite, titanite, and epidote-allanite, whereas in hematite-rich assemblages, REEs occur in apatite (Mazdab et al., 2008). A broad distinctive minor element composition is apparent in IOCG deposits with higher concentrations of many critical commodities, such as REEs, U, and Co. The total REE content in these deposits is generally reported as 0.2–3%, whereas it exceeds 10% in some rare occasions (Mazdab et al., 2008).

2.1.5. Vein and skarn deposits

Occasionally, REEs are enriched in vein and skarn systems, which are not intimately associated with alkaline igneous rocks or carbonates. Despite having small tonnages, these deposits contain high TREO grades and they are mostly LREE-dominated. The deposits in the Bastnäs area in Sweden are considered as the widely known occurrence of REE-enriched veins and skarns (Holtstam et al., 2014). Other occurrences of this type of deposits are the vein deposits at Steenkampskraal in South Africa and Gakara in Burundi (Harmer and Nex, 2016). Bastnaesite and monazite (Table 2) are the main REE-bearing minerals found in these deposits. For example, the Steenkampskraal deposit consists of about 40% monazite in the main mineralization zone (Harmer and Nex, 2016). Although vein and skarn deposits have been attractive for exploitation due to their high grades, they may impose radioactive threats during processing due to high Th concentrations (Goodenough et al., 2018).

2.1.6. Placers

Placers have been considered as valuable REE resources for a long time, particularly monazite mineral sand in India and Australia (Sengupta and Van Gosen, 2016). Placer deposits are natural accumulations of valuable minerals by gravity separation during sedimentary processes and generally are classified as alluvial, colluvial, eluvial, beach placers, and paleo placers. These placer deposits commonly occur in streams and rivers, beaches, and shallow marine environments (Haldar, 2013). Most REE-bearing placers are Tertiary or Quaternary deposits derived from sources associated with granitic or high-grade metamorphic rocks. However, paleo placers that are old as Precambrian rocks also contain significant concentrations of REEs. Orris and Grauch (2002) identified more than 360 REE-enriched placers, worldwide, such

as tin-rich river placers in Malaysia, paleo-placers in Witwatersrand in South Africa, Elliot Lake in Ontario, and beach sand deposits in Kerala, Andhra Pradesh, Tamil Nadu, and Odisha in India.

The most common economic minerals found in placer deposits are ilmenite, rutile, magnetite, zircon, monazite, and xenotime. Although placer minerals are mostly processed to produce titanium (Ti) or Sn, the majority of them are capable of producing REEs as a by-product (Goodenough et al., 2018). Monazite, the major RE mineral found in placer deposits is highly enriched in LREEs over HREEs. However, monazite contains HREEs, such as Tb, Dy, and gadolinium (Gd) and these are rarer and less concentrated in ore deposits comparing to other HREEs (Balaram, 2019). The degree of RE mineral enrichment in these placers depends on the source of eroded sediments. In addition to alkaline igneous rocks and other REE deposits, most common igneous rocks, metamorphic, and even older sedimentary rocks are considered as sources since they contain enough monazite for accumulation. However, placers usually contain high concentrations of radioactive elements, such as Th and U, making the REE extraction process difficult and problematic (Zhou, 2017a).

2.1.7. Laterites

Laterites are defined as residual soils formed by deep weathering of rocks under tropical and subtropical climatic conditions. Generally, they are enriched in hydrated iron and aluminum oxides (Ugbe, 2011). However, laterites could have concentrated with REE-bearing minerals, if they had derived from REE-hosted rocks, such as carbonatites, pegmatites, and granites. If the weathering profiles are developed on igneous or meta-igneous rocks, REEs could be remobilized into secondary minerals, which are concentrated in particular layers within the profile (Berger et al., 2014). These weathered layers can be considered as REE resources. For instance, a highly REE-enriched laterite layer about 70 m thick was observed at Mt Weld mine in Australia and it was formed by weathering of carbonatite (Jaireth et al., 2014). This laterite zone consists of diversified RE minerals, such as monazite, churchite, and plumbogummite-group minerals (Table 2) (Lottermoser, 1990). In addition, REE-bearing laterite deposits are found in Brazil, South Africa, and Western Australia (Long et al., 2012).

2.1.8. Ion adsorption clays

Ion adsorption clay deposits, limited to a few specific localities (e.g. China), are considered as an economic REE resource in the world, especially for HREEs due to the feasibility of REE separation (Sanematsu and Watanabe, 2016; Ilankoon et al., 2018). Therefore, REEs in these deposits can be easily leached out at ambient temperature using ammonium sulphates (Bao and Zhao, 2008; Moldoveanu and Papangelakis, 2012; Li et al., 2017).

However, despite their significance in the world's HREE supply, the ore forming processes of these deposits are poorly understood. It was supposed that ion adsorption clay deposits are formed through the adsorption of REEs from lateritic sections into clay minerals (e.g. kaolinite and halloysite), instead of being remobilized into secondary minerals. A clear understanding of the genesis of ion adsorption clays could also be important to identify the deposits in other parts of the world (Li and Zhou, 2020). Ion adsorption clay deposits are mainly classified into LREE- and HREE-dominated types and HREE-enriched deposits are only hosted by granites, most probably of A-type affinity. REE concentrations up to 4000 ppm are observed in ion adsorption clay deposits along with a significant variation within the weathering profile. In addition to China's ion adsorption clays, a few other occurrences have been discovered and explored in the continents of Southeast Asia, Africa, Serra Verde in Brazil and Tantalus in Madagascar (Moldoveanu and Papangelakis, 2012). However, the current status of these identified deposits, including commercial extraction of REEs, are not explicitly reported.

Currently, only Southern China and a few other localities in northeastern Myanmar are engaged in mining of ion adsorption clays

(Wang et al., 2017; Ilankoon et al., 2018), mostly for HREEs, and the deposits in China are considered as the world's main source of HREEs. Ion adsorption clay deposits of China are concentrated in Southern Jiangxi and Hunan, northern Guangdong, eastern Guangxi, and western Fujian and Yunnan Provinces. They are mostly hosted in weathered soils of alkaline granites with grades ranging from 0.05 to 0.2 wt% REOs (Sanematsu and Watanabe, 2016; Wang et al., 2017). Generally, these parent rocks are subjected to immense late-stage alteration by F-rich fluids, which converted primary HREE-bearing accessory minerals, such as xenotime and zircon to weathering-susceptible HREE minerals like synchysite-(Y) and gadolinite-(Y) (Table 2) (Li et al., 2019).

Although more than 170 ion adsorption deposits are found and exploited in China, most of them have been closed due to environmental issues (e.g. surface vegetation clearing, soil excavation and subsequent soil erosion, and disposal of waste water and tailings) caused by commonly used tank/heap leaching techniques and informal mining activities (Ilankoon et al., 2018).

2.1.9. Offshore sources

Seawater, marine sediments, and phosphorites were identified as potential marine sources of REEs (Goldberg et al., 1963). According to Goldberg et al. (1963), a seawater sample collected off the coast near San Diego, California showed an average REE concentration of 7.1×10^{-7} ppm. Deng et al. (2017) reported that the REE concentration in seawater of the western Pacific region is about $(5.724\text{--}30.240) \times 10^{-7}$ ppm. REE concentration proportionally increases with the depth of sea water, whereas LREE enrichment is higher compared to HREEs. Moreover, REE concentrations in seawater differ at different locations. For example, seawater RE content in the deep Pacific Ocean is greater than that of the deep Atlantic Ocean (Elderfield and Greaves, 1982).

Large marine phosphorites such as the ones in Florida and Idaho are enriched in extensive quantities of REEs and other strategic metals such as U and Th (Altschuler et al., 1967). Marine phosphorites are typically formed in very shallow, near-shore marine or low energy environments, such as estuarine, supratidal zones, and littoral or intertidal zones (Filippelli, 2011). They occur as nodules (spherical concentrations of phosphates that are randomly dispersed), bone beds (concentrations of phosphates as beds, which contain small skeletal particles and coprolites) and rarely as phosphatizations (phosphate enriched-fluids, that are leached from guano) (Filippelli, 2008). Marine phosphorites are rich in marine apatite, where REEs occur in trace quantities, with a weight percentage of 0.01 to 0.1. Marine apatite contains higher concentrations of HREEs than LREEs. Major occurrences of marine phosphorites were identified, namely, the Bone Valley Formation in central Florida, Phosphoria Formation in Idaho and Montana, northern Florida, and North Carolina (Altschuler et al., 1967).

In addition to the aforementioned marine REE deposits, iron-manganese nodules in the Pacific Ocean have higher concentrations of HREEs, even more than that of the carbonatite deposits. Moreover, deep-sea mud in the Pacific Ocean is considered as a low grade REE resource in addition to its low Th content (Hein et al., 2011; Kato et al., 2011). Although REEs are not extracted from these marine sources to date, they will become a promising source in the future as terrestrial REE sources alone would not be adequate to cater for the escalating REE demand.

2.2. Global distribution of REE resources

Currently, the total amount of global REE resources is estimated to be 478.14 million tonnes (Fig. 2), and those are distributed in China (164 million tonnes), Brazil (55 million tonnes), Australia (49 million tonnes), Russia (48 million tonnes), Greenland (43 million tonnes). The remaining 119 million tonnes belong to Canada, Sweden, USA, and Vietnam (Zhou, 2017b). However, all these resources are not employed to produce REEs and REE resources, which are in the production stage

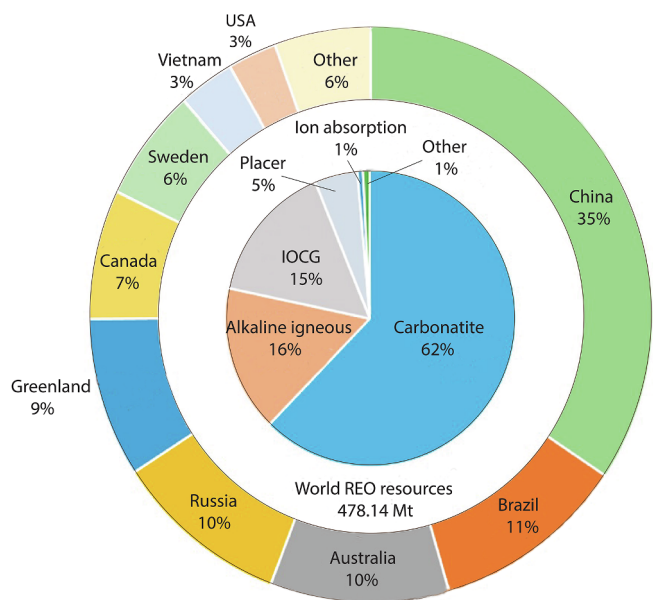


Fig. 2. The distribution of global rare earth resources according to deposit types and countries of origin ().
Source: Zhou, 2017a

Table 3
The distribution of global REE reserves (U.S. Geological Survey, 2019).

Country	Reserves in tonnes (in terms of REOs)	% Share
United States	14,00,000	1.17
Australia	34,00,000	2.83
Brazil	2,20,00,000	18.33
China	4,40,00,000	36.67
India	69,00,000	5.75
Malaysia	30,000	0.025
Russia	1,20,00,000	10
Vietnam	2,20,00,000	18.33
Other countries	44,00,000	3.67
Total World Reserves (rounded)	12,00,00,000	-

are considered as REE reserves (Orris and Grauch, 2002; US Geological Survey, 2019). According to the published data in the United States Geological Survey (USGS), the total amount of world’s REE reserves are about 120 million tonnes (US Geological Survey, 2019) (Table 3).

The global REE resources (i.e. 478.14 million tonnes) are dominated by carbonatite deposits containing 297.6 million tonnes within 66 deposits, and the rest is alkaline igneous rocks, iron oxide copper-gold (IOCG) deposits, placers, and ion adsorption clays (Zhou, 2017b) (Fig. 2).

3. Geological settings of Sri Lanka

Sri Lanka is a tropical island that is located 32 km away from the east of the southernmost extremity of Peninsular India. The total area of Sri Lanka is approximately 65,600 km², and the island is 432 km long and 224 km wide at its greatest breadth. Geologically, more than 90% of Sri Lanka comprises Precambrian high-grade metamorphic rocks, whereas the remaining is composed of sedimentary rocks and minor igneous intrusions (Cooray, 1984).

3.1. Precambrian rocks of Sri Lanka

Precambrian rocks mainly compose of metamorphosed sediments (para-gneisses) and meta igneous rocks (orthogneisses). Major rock types found in the high-grade metamorphic rock terrain are quartzites,

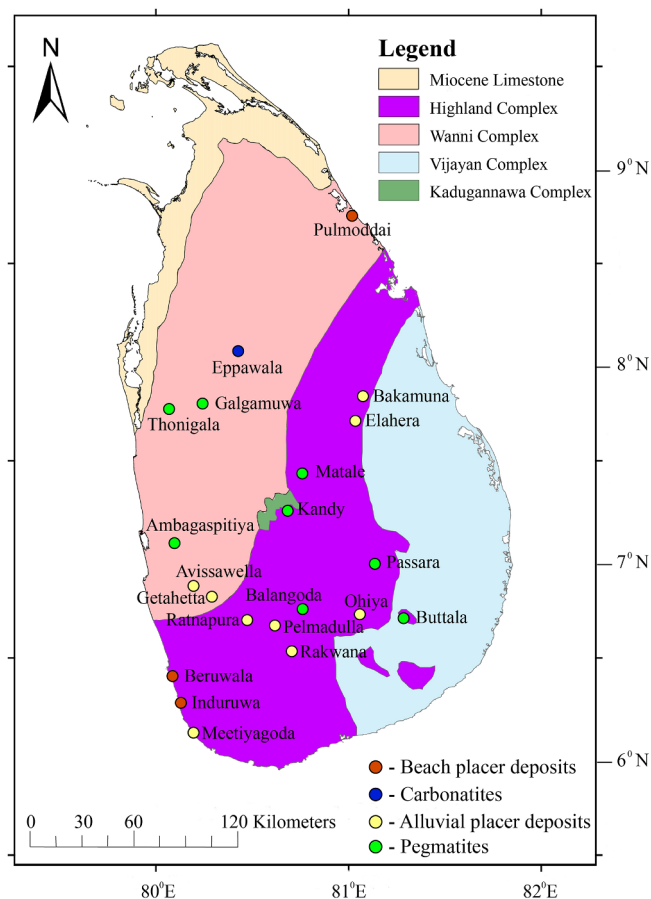


Fig. 3. Simplified geological map of Sri Lanka illustrating major lithotectonic subdivisions and potential REE resources (Source: modified from Cooray, 1994).

high-grade gneisses and granulites, calc gneisses and granulites, crystalline limestones (marbles) and dolomites, charnockite, and pelitic gneisses. Moreover, these rocks contain certain economic minerals, such as ilmenite, zircon, sillimanite, REE-bearing minerals, thorium minerals, and precious and semi-precious gems stones (Fernando, 1986). The metamorphic terrain has been subdivided into three major lithotectonic complexes (Fig. 3), namely, Highland Complex (HC), Vijayan Complex (VC), and Wannai Complex (WC) on the basis of geochronology and metamorphic grade (Kröner, 1991; Cooray, 1994).

The largest unit, HC including the Kataragama, Kudu Oya, and Buttala granulite inliers (Fig. 3), consists of supracrustal rocks and miscellaneous igneous intrusions of mostly granitoid composition. In this complex, rocks of magmatic origin were widely spread and pre- to syn-metamorphic granitic intrusions occur frequently (Kröner et al., 1991; Pohl and Emmermann, 1991). The VC, located in the eastern and southeastern parts of Sri Lanka (Fig. 3), comprises biotite-hornblende gneisses, scattered bands of meta-sediments, and granitic gneisses. In addition, small plutons of granite and acid charnokites and NW-trending suite of dolerite dikes are found in the Vijayan domain (Jayawardena and Carswell, 1976). The WC (Fig. 3) predominantly consists of granitoid gneisses, charnockitic gneisses, and granites with rare intercalations of metasediments, mainly calc-silicate rocks and quartzites. Another one is the Kadugannawa Complex (KC), which is located around Kandy in the Central Highlands of Sri Lanka (Fig. 3). It is mainly composed of hornblende and biotite-gneisses with minor supracrustal rocks (Kröner et al., 1991; Pohl and Emmermann, 1991).

3.2. Quaternary deposits in Sri Lanka

Quaternary deposits are considered as consolidated and unconsolidated material including laterites, gravels, sands, and clays formed on the surface of the Miocene. These deposits are categorized into two periods, namely, Pleistocene and Recent (Fernando, 1986). Red Earth along the north-west coast aligning in the north-south direction belongs to the Pleistocene period (Cooray, 1984). Red Earth contains small quantities of heavy minerals, such as ilmenite, zircon, and monazite. Laterite is also a Pleistocene deposit, which is a mottled deep red, yellow or reddish-brown ferruginous earth exhibiting vesicular structure. Laterites are more prominent in Colombo district and along the south-west coast from Matara to Thangalle. The Recent Quaternary deposits in Sri Lanka include residual, alluvial, coral and shell formations, lagoons, estuaries, peat, gem-bearing gravels, and beach mineral sands (Fernando, 1986).

4. REE potential of Sri Lanka

Monazite with Ce in gem gravels was detected during a mineral survey in 1914 in Sri Lanka and it was the first RE mineral detection in Sri Lanka (Jayawardena, 2011).

According to Pohl and Emmermann (1991), there are relatively high REE concentrations (particularly LREEs) in the Precambrian rocks of Sri Lanka (Table 4). For a long time, Sri Lanka has been renowned for its large deposits of monazite in the onshore areas of Beruwala and Pulmoddai (Fig. 3) (Jayawardena, 2011). Since monazite is one of the major REE-bearing minerals, aforesaid areas might be enriched in REEs. Gem-bearing gravels are also identified as a promising source of REEs due to the presence of constituents like Th, U, Y, Nb, Ti and beryllium (Be) (Wadia and Fernando, 1945a). However, bastnaesite, the predominant RE mineral, has not yet been discovered in Sri Lanka. Bastnaesite commonly occurs in carbonatites, pegmatites, and quartz veins, and therefore, such potential bastnaesite sources can be found in Sri Lanka.

The chemical composition of different geological formations and mineral resources have revealed the RE potential of Sri Lanka (Table 4), particularly in the Precambrian terrain. However, detailed studies on REEs have not yet been carried out to explore or quantify these minerals, including economic feasibility. Therefore, detailed explorations are recommended in Sri Lanka, covering all the potential REE sources.

4.1. Carbonatites

In 1971, the Geological Survey Department of Sri Lanka discovered a carbonatite occurrence at Eppawala in the North Central Province

(Fig. 3), and it was the first recorded occurrence of carbonatite in Sri Lanka (Jayawardena et al., 1978). This is the only known carbonatite occurrence in Sri Lanka to date (Pitawala and Lottermoser, 2012). The Eppawala carbonatites occur in high-grade meta-sedimentary and igneous rocks of the Precambrian Wannai Complex (Fig. 3) as massive intrusions (Pitawala et al., 2003). The origin of this carbonatite is explained using different theories. Magmatic origin was suggested since it contains high concentrations of phosphorous (P), strontium (Sr), Rb, Nb, La, and Y. In contrast, it could have been a marble, which was subjected to mobilization and moved to the current position (Cooray, 1984). It is also supposed that the secondarily developed thick phosphate-rich regolith was formed by intense tropical weathering of the parent carbonatite rock (Hewawasam, 2013).

In geological terms, this area is characterized with three broad lithological zones, namely, a prominent hornblende biotite gneiss zone, granites, and granite gneiss with or without pink feldspar adjacent to carbonatite complex and charnockites with minor quartzites together with granites and granitic gneisses (Fig. 4). In addition, synformal and antiformal structures are evident within the area (Fig. 4). The deposit is located in the middle of a synformal structure (Pitawala et al., 2003). The carbonatite rock at Eppawala contains primary minerals, such as calcite (about 90% of the total carbonate content), dolomite (5–9%), and magnesite (as an accessory carbonate mineral) in the form of subhedral and anhedral grains. In the whole-rock geochemistry of Eppawala carbonatites, CaO is the main constituent (42–53 wt%) while SiO₂ shows markedly low concentrations (< 0.4 wt%). MgO content varies between 2 and 9 wt%. P₂O₅ content exhibits a notable variation (0.01–10.5 wt%), whereas Fe₂O₃ content varies from 0.3 to 1.2 wt%. Other oxides, such as Na₂O (0.02–0.05 wt%), K₂O, TiO₂, Al₂O₃ (< 0.01 wt%) and MnO (< 0.1 wt%) are also found in very low concentrations (Pitawala et al., 2003).

Numerous geochemical studies on Eppawala carbonatites show the presence of REEs and RE minerals such as monazite and apatite (e.g. Dahanayake and Subasinghe, 1991; Pohl and Emmermann, 1991; Pitawala et al., 2003; Manthilake et al., 2008). Table 5 presents the data of REEs in Eppawala carbonatites and according to Fig. 5, the REE distribution pattern of Eppawala carbonatites resembles the REE variation of the average carbonatites in the world. Moreover, Eppawala carbonatites contain higher concentrations of LREEs than HREEs with a varying La/Yb ratio between 12 and 86. According to the primitive mantle normalization (Fig. 5), LREEs are relatively enriched in Eppawala carbonatites (Manthilake et al., 2008).

The phosphate-rich regolith is covering about 20 km² with a thickness of 50 m (Dinalankara, 1995). This regolith has two horizons, namely, leached zone (20–50 m in thickness, hard and consolidated, primary apatite crystals are implanted in a secondarily formed matrix)

Table 4

REE distribution (ppm) in different geological and other formations of Sri Lanka (Sources: Senaratne et al., 1987; Pohl and Emmermann, 1991; Pitawala et al., 2003; Athurupane, 2014).

REEs	Metamorphic rocks	Charnokitic gneiss	Granitic gneiss	Granitoid Intrusion	Carbonatite	Residual	Blackish Brown Stream Bed Sediments	Buried Alluvial Deposits
Y	37	39	43	67	57	–	–	–
La	44	44	47	165	151	55.1	79.2	53
Ce	105	98	123	317	354	127	158	252
Pr	10	10	14	33	48.9	14	–	14.3
Nd	36	36	48	102	192	48.4	66.5	32.9
Sm	8.5	6.9	10.9	15.9	31.5	9	11.8	7.8
Eu	1.52	1.38	2.95	2.04	7	1.7	2.3	1.3
Gd	7	5.8	12.3	14.6	20.1	–	–	–
Dy	6.9	5.2	13.2	11.7	1.8	7.5	7.9	–
Ho	1.54	1.06	3.35	2.23	10.2	1.5	–	1
Er	4.3	3.1	9.5	6.4	1.8	–	–	–
Yb	4.3	2.58	9.63	5.3	0.6	4.4	4.3	2.3
Lu	0.67	0.45	1.56	0.8	3.5	0.6	0.7	0.4
Th	13	5	14	45	0.6	–	–	–
Total REEs	279.73	258.47	352.39	787.97	885.3	270.5	332	366

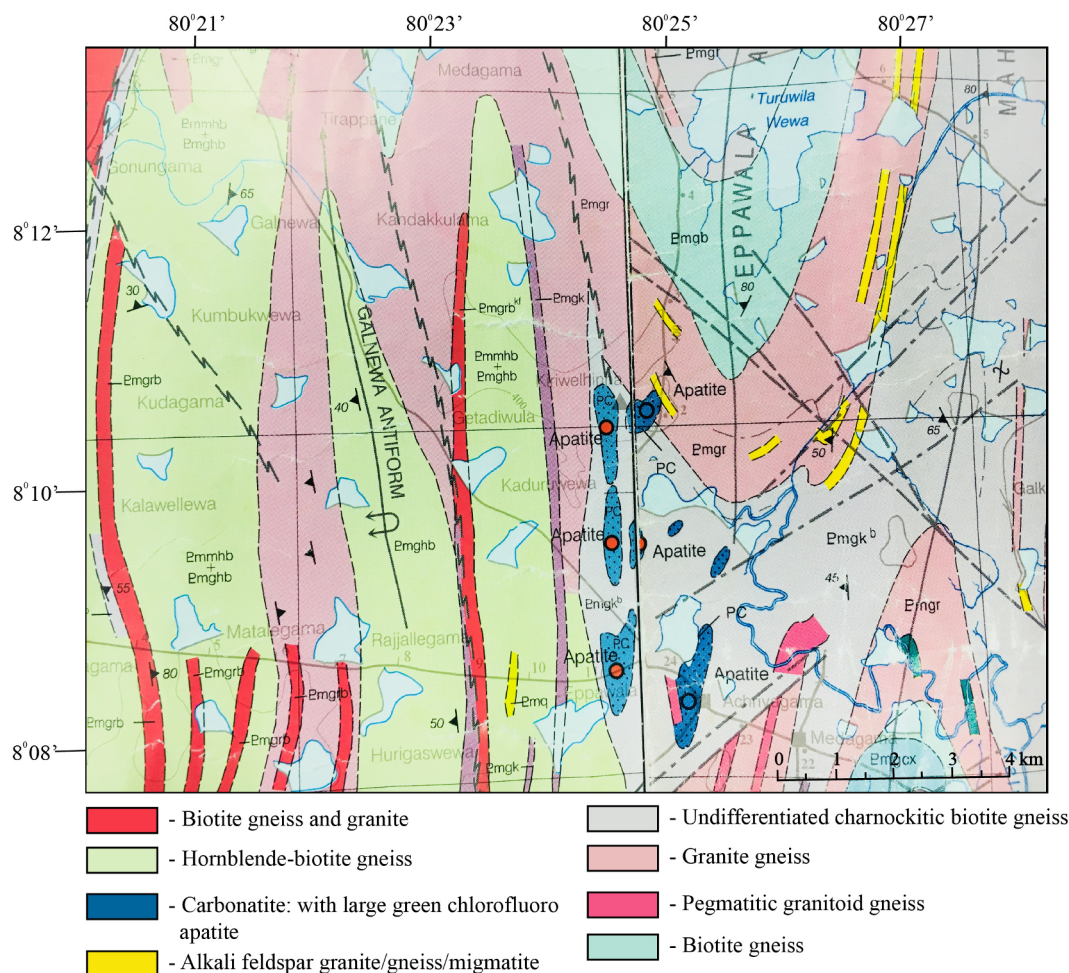


Fig. 4. Geological map of Eppawala area in Sri Lanka (). Source: GSMB, 2001

and weathered top zone (2–40 m in thickness, deeply decomposed, residual apatite crystals are embedded in the soft matrix) (Dahanayake and Subasinghe, 1989; Subasinghe, 2013). Overall, regolith mainly consists of chloro-fluor-hydroxyapatite along with secondary products, such as fluorapatite and carbonate-fluorapatite. However, these apatite minerals have been progressively weathered to form minerals, such as millisite, crandallite, and wavellite. As a result, chloro-fluor-

hydroxyapatite and fluorapatite are dominantly found in the coarse sands of the matrix, whereas millisite, crandallite, and wavellite are found in the finer fraction (Hewawasam, 2013). In addition to the phosphate-bearing minerals, the secondarily formed matrix in the regolith contains minerals like hematite, goethite, quartz, rutile, ilmenite, spinel, and magnetite. Since carbonate minerals in the bedrock are completely dissolved during the weathering, calcite and dolomite do

Table 5
REE abundances (ppm) in the samples from Eppawala carbonatites and apatites (1–5 indicates sample numbers) (Manthilake et al., 2008).

REEs	Carbonatites Samples					Apatite Samples				
	1	2	3	4	5	1	2	3	4	5
Y	33.9	25.6	29.8	40.2	53	69	72.6	72.9	75.8	87.5
La	98.8	33.1	91.5	197.99	383.97	510.33	576.82	546.58	574.23	739.99
Ce	235	92	207	469	866	1217	1363	1289	1349	1714
Pr	31	14	27	57	108	156	173	163	170	216
Nd	129.5	66.8	112.5	235.5	434.9	636.7	700.7	654.3	676.3	856
Sm	21.7	13.2	18.3	36.06	62.2	92.07	101.83	92.68	97.55	120.83
Eu	4.61	2.15	3.25	7.65	13.71	17	19.12	17.42	18.36	22.62
Gd	13.4	9.49	11.4	20.11	32.82	49.54	53.62	48.45	50.49	59.9
Tb	1.38	0.99	1.18	1.96	3.09	4.36	4.8	4.46	4.67	5.45
Dy	6.45	4.64	5.5	8.42	12.7	17.8	18.9	18.4	18.8	22.33
Ho	1.11	0.84	0.97	1.36	1.96	2.63	2.77	2.73	2.79	3.32
Er	2.87	2.22	2.53	3.3	4.48	5.67	6.02	5.94	6.14	7.17
Tm	0.39	0.3	0.34	0.4	0.53	0.62	0.65	0.66	0.68	0.79
Yb	2.49	1.97	2.25	2.51	3.19	3.58	3.74	3.78	3.86	4.51
Lu	0.36	0.29	0.35	0.34	0.41	0.4	0.41	0.42	0.44	0.51

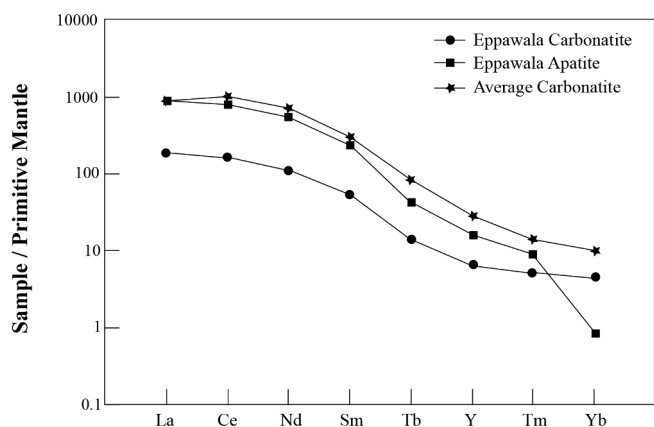


Fig. 5. Primitive mantle normalised REE variations of Eppawala carbonatites and apatites (i.e. REE concentrations ratio of the sample and primitive mantle) (Source: Manthilake et al., 2008). Normalizing values from Sun and McDonough (1989). Average carbonatites contents from Woolley (1989) are included for comparison.

not appear in the regolith. Goethite in the regolith is formed after enstatite weathering followed by iron oxide weathering. Ilmenite, spinel and magnetite are moderately resistant to weathering and therefore these minerals are accumulated in the regolith (Hewawasam, 2013).

Due to the availability of LREEs in carbonatite bedrock, LREEs are sometimes substituted within the lattice of the aforesaid phosphate-bearing minerals during the formation or later hydrothermal alteration and form REE-bearing minerals, such as monazite. Therefore, apatite crystals contain monazite inclusions, which show high concentrations of LREEs (Table 5), especially La, Ce, and Nd. Moreover, apatite has a high LREE/HREE ratio ranging from 102 to 118 (Manthilake et al., 2008). Therefore, it is essential to carry out prospecting studies for REEs in the Eppawala carbonatite. LREE enrichment in both apatite crystals and carbonatite rock favors mining of this deposit for both phosphates and LREEs. In addition, Jaya-Ganga, a man-made water canal, flows across the Eppawala carbonatite and transport materials derived from the deposit. These materials are accumulated in downstream lake sediments and show relatively high concentrations of La and Ce (i.e. 64 and 130 ppm, respectively) (Dushyantha et al., 2017; Dushyantha et al., 2019). Therefore, downstream lake sediments could also be considered as a secondary source for La and Ce, however, further explorations need to be carried out.

4.2. Pegmatites

The majority of pegmatites and hydrothermal deposits in Sri Lanka occur in Matale district located in the central part of the HC. It has been considered as the oldest metamorphic unit in the Sri Lankan crust (Fig. 3). Moreover, there are many other pegmatite occurrences found in different localities in Sri Lanka (Fig. 3) and most of which cross-cut the Precambrian high-grade metamorphic rocks (Fernando et al., 2011). Although only a few studies have been carried out for the evolution, mineralization and geochemistry of pegmatites and hydrothermal deposits in Sri Lanka, it has been inferred that most of the pegmatite, dolerite, carbonatite, and granite bodies are formed by a post-peak metamorphic event as magmatic and hydrothermal activities (Pitawala et al., 2003; Pitawala et al., 2008). In addition to the pegmatites in the Matale area, magnetite-bearing pegmatites are found in Balangoda, Kandy, Buttala, Passara, and Galgamuwa area within the Thonigala complex within the HC and WC complexes as intrusive bodies. Another granitic rock complex within metamorphic terrain was discovered in Thonigala (northwest Sri Lanka) and Ambagaspiya (western Sri Lanka) in WC. However, these granitic occurrences were found as in-situ melt formed during metamorphism (Fig. 3). The south-

west of Sri Lanka also has pegmatite occurrences with radioactive REE minerals, such as monazite and allanite (Cooray, 1984).

The pegmatites in Matale district are both magmatic and hydrothermal deposits, which mainly contain quartz, feldspar (both Alkali and plagioclase), biotite mica, lepidolite mica, hornblende, and several fluoride bearing minerals, such as topaz and fluorite. The area is composed of rocks with both meta-sedimentary and meta-igneous origins. Meta-sedimentary and meta-igneous rock intercalations are visually observed within the entire area. The middle part of Matale district around Owala, Kavudupellella towards Nalanda contains pegmatites and hydrothermal deposits with high fracture intensity. Mainly, there are two types of pegmatite occurrences in Matale district. The first type is narrow (generally 1 m wide) concordant or discordant bodies that occur as dykes, lenses, pods, and veins in high-grade metamorphic rocks. It shows a wide variation of composition from felsic to mafic while contacts with the host rock is mostly gradational or irregular. Moreover, these structural features are formed by the partial melting of high-grade rocks. The second group is large pegmatitic plutons with mega crystals of feldspars, quartz, and mica. Several pegmatites in this group contain topaz and fluorite as well. There are more than 50 of these large individual pegmatite bodies in Matale district and a few of them have been investigated (Fernando et al., 2011). The aforementioned second group of pegmatite bodies highly vary in size and shape (i.e. circular, lenticular, or rarely oval bodies). According to their modes of occurrences and petrography, it was interpreted that these are formed by magmatic activities (Pitawala et al., 2008).

Pegmatites of Sri Lanka comprise quartz, feldspar, and mica. Some of these pegmatites are considered as economic deposits for phlogopite and muscovite mica, whereas others are mined for feldspar (Cooray, 1984). Generally, mafic granulites contain mainly garnet (~30%), orthopyroxene (~40%), clinopyroxene (~10%), plagioclase (~8%), with subordinate ilmenite (~1%) and biotite (~3%). However, major mineral assemblages present in the pegmatites of Matale district are garnet, orthopyroxene, biotite, and feldspar (Fernando et al., 2011). Pegmatite deposits in Matale and Kandy areas range from small to very large deposits, and the deposit at Kaikawala is considered as the largest one (Nawaratne, 2009). According to Cooray (1984), pegmatites found in Owala area contain allanite (Table 2), which is a primary RE mineral. It was found that this minor allanite deposit in Owala, Matale contains about 15–20% of REEs (Daily FT, 2016). Although a few petrological, mineralogical, and geochemical studies have been carried out in these pegmatite occurrences (e.g. Pitawala et al., 2003, 2008; Fernando et al., 2011), REE prospecting studies are not yet carried out. Since pegmatite is considered as a global REE resource, these pegmatite occurrences in Sri Lanka, especially those in Matale district, should be studied in detail to assess their REE potential.

4.3. Beach placer deposits

The coastline of Sri Lanka (particularly northeast and southwest) is rich in heavy mineral beach placer deposits and some of them (e.g. Pulmoddai mineral sand deposit, and Beruwala placer deposit) have been identified as economically important. Generally, heavy minerals occur near estuaries, in isolated bays, around barrier bars, and in raised beaches. Moreover, monazite rich deposits also tend to occur beneath inter-barrier swamps closer to the coastline. Monazite rich heavy mineral concentrates are usually found in irregular bands with different concentrations either on the surface or under a layer of light coloured barren sand. These heavy mineral placers mostly consist of ilmenite, zircon, monazite, and garnet, whereas rutile, sillimanite and spinel are found in minor quantities. However, pyroxenes, hornblende, tourmaline, allanite, and thorianite are quite rare in these beach placers (Wickremeratne, 1986). According to Rupasinghe et al. (1983), sources for the monazite rich placer deposits may be highly metamorphosed aluminous schists and gneisses along with granitoid rocks of the HC

Precambrian terrain, particularly of the southwest part. The metamorphosed HC Precambrian rocks are enriched in REEs (Table 4), and therefore, monazite rich placer deposits of Sri Lanka can be considered as probable REE resources.

The Pulmoddai (Fig. 3) is the largest heavy mineral beach placer deposit in Sri Lanka, which is located at the northeast coast. The Pulmoddai deposit possesses a great potential as a valuable REE resource to the country (Gamage, 2018). It is situated at 54 km north from the Trincomalee bay and extends from Nilaveli to Kokilai lagoon mouth with a length of about 7.4 km and an average width of 150 m. The Pulmoddai deposit is considered as one of the richest mineral sand deposits in the world since it is the only deposit that contains more than 80% of usable heavy mineral sands (Amalan et al., 2018). The main source of this deposit may be weathered and eroded hard rocks, transported through Mahaweli River, which is the longest river (335 km) in Sri Lanka covering about one sixth of the island. Moreover, the drainage basin of the Mahaweli River covering an area about 10,448 km² is composed of HC metamorphic rocks, which are known to have significant REE concentrations (Udarika et al., 2016; Weththasinghe et al., 2020). The secondary source of these heavy minerals could be offshore sediments, and it is supposed that the sediments are mechanically accumulated in the northeast coast by means of ocean waves and currents (Amalan et al., 2014). The Pulmoddai deposit is continuously replenished and if not mined, it is washed off into the sea during the monsoons.

According to the estimations, the Pulmoddai deposit contains about 6 million tonnes of heavy mineral sands comprising of 70–72% ilmenite, 8–10% zircon, 8% rutile, 0.3% monazite, and 1% sillimanite (Thilakanayaka, 2015). Moreover, the deposit has been valuable due to its economic concentrations of monazite and the estimated monazite recovery is 300 tonnes per annum. REE content in the Pulmoddai monazite is over 61% and the most abundant elements are Ce, La, and Nd with abundances about 28%, 15%, and 10%, respectively. In this regard, about 3.87 g of Ce can be produced by using 1 kg of Pulmoddai mineral sand (Gamage, 2018). According to Gamage (2018), RE concentrations in the Pulmoddai mineral sands are presented in Table 6.

In this context, Pulmoddai monazite clearly portrays the highest potential of recovering REEs in Sri Lanka. However, economically viable RE processing methods are yet to be established in both lab-scale and industrial-scale. In addition, disposal of radioactive contaminants, such as Th and U needs to be handled sustainably during the processing. The authors recommend studies in detail to recover REEs from the Pulmoddai mineral sand deposit. Moreover, it should be one of the prioritize areas in the Sri Lankan mining and minerals industry rather

Table 6

REE analysis (ppm) of the Pulmoddai deposit (Gamage, 2018). (There are several samples, which are indicated as Sample A, Sample B, Sample C, and Sample D).

REEs	Monazite			
	Sample A	Sample B	Sample C	Sample D
Y	4906	4832	4283	4308
La	49,005	48,041	59,372	59,758
Ce	91,160	89,765	110,643	111,693
Pr	9784	9586	12,154	12,117
Nd	33,621	32,621	41,873	42,103
Sm	5469	5325	6937	6887
Eu	168	158	224	222
Gd	7300	7087	9413	9368
Tb	817	779	1061	1062
Dy	1173	1125	1536	1544
Ho	165	157	217	218
Er	1396	1323	1459	1451
Tm	13	12	17	17
Yb	330	313	435	435
Lu	77	73	102	102

Table 7

Analyses of Monazite deposits in Sri Lanka (Fernando, 1986). Chemical compositions of the Indian and Brazilian Monazite deposits are included here for comparison. Concentrations are in ppm.

Constituent	Beruwala	Dondra	Indian	Brazilian
ThO ₂	8.65	9.51	9.5	6.5
U ₃ O ₈	–	–	0.35	0.17
(RE) ₂ O ₃ *	–	–	58.60**	59.20**
Ce ₂ O ₃	27.35	28.7	27.2	26.8
La ₂ O ₃	31.08	28.56	–	–
Y ₂ O ₃	0.95	1.05	–	–
Fe ₂ O ₃	0.15	0.1	0.8	0.51
Al ₂ O ₃	0.78	1.31	–	–
CaO	0.2	0.89	–	–
TiO ₂	0.15	0.05	0.2	1.75
P ₂ O ₅	27.5	28.91	29.1	26
SiO ₂	1.6	–	1.45	2.2

* Total rare earths (Ce, La and Y).

** includes ceria (Ce₂O₃).

than exploiting Pulmoddai heavy mineral sands as raw materials.

In addition to the Pulmoddai mineral sand deposit, the southwestern coast has also been known for a long time for its occurrence of monazite rich heavy mineral placer deposits. These placer deposits have been studied by many researchers and economic exploitation had been carried out since 1918 (e.g. Fernando, 1954; Wadia and Fernando, 1945b). A thick monazite enriched stretch was found along the southwestern coast mainly due to the effects of southwestern monsoon. Therefore, high monazite concentrations are evident in placer deposits at Beruwala, Kaikawala, Polkotuwa, and Induwara (Fig. 3). The Beruwala deposit is 1 km long and located in a small bay formed by the headlands of Beruwala and Maggona. The Kaikawala deposit is also about 1 km long with a 10 m width and is a part of a narrow beach that forms the two headlands. Those contain an average of 4–20% monazite and 450 tonnes were collected from these deposits from 1918 to 1922. Although these deposits were assumed to be exhausted, during the period of 1957–1971, the Beruwala deposit produced about 500 tonnes of monazite (Wickremeratne, 1986). A comparison of the chemical composition of monazite in Beruwala, and Dondra with the Indian and Brazilian deposits is presented in Table 7 (Fernando, 1986).

According to the preceding discussion, there are significant REE concentrations in beach placer deposits in Sri Lanka, especially Pulmoddai heavy mineral sand deposit. Therefore, beach placer deposits could be considered as one of the potential REE resources in Sri Lanka.

4.4. Alluvial placer deposits

The heavy mineral fraction of stream sediments in Sri Lanka contains several radioactive minerals, including monazite, zircon, thorianite, thorite, and allanite, which are concentrated with REEs, U, Th, and some other trace elements (Chandrajith et al., 2000). According to the geochemical studies carried out in Walawe river, about 50% of the stream sediments were heavy minerals, including zircon, garnet, monazite, ilmenite, sphene, allanite, magnetite, rutile and ferromagnesian minerals (Chandrajith et al., 2000, Ratnayake et al., 2017). In addition, Rupasinghe et al. (1994) found several RE containing minerals, such as davidite and monazite in the stream sediments from the Ratnapura area.

Based on Rupasinghe et al. (1983), the stream sediments of Bentota river in the southwest of Sri Lanka, is also enriched in Th rich monazite, particularly at the river mouth. Ilmenite, garnet, zircon, and monazite were also found as heavy minerals and the ilmenite content was 30–71%. The stream sediments of Bentota river and its associated tributaries thus contain high concentrations of REEs with a pronounced Eu anomaly (Table 8). Moreover, these stream sediments are enriched

Table 8
REE enrichment of sediments in Bentota river and associated tributaries ().
Source: [Rupasinghe et al., 1983](#)

Oxides and trace elements	Concentration (wt%, ppm)
Ce ₂ O ₃ (REOs)	30.45%
P ₂ O ₅	24.50%
La ₂ O ₃ (REOs)	14.56%
Nd ₂ O ₃ (REOs)	12.48%
ThO ₂	9.49%
Pr ₆ O ₄ (REOs)	3.62%
Sm ₂ O ₃ (REOs)	1.64%
K ₂ O	1.21%
ZrO ₂	1.35%
Gd	7500 ppm
Ba	5000 ppm
U	3640 ppm
Cr	2000 ppm
Cl	2000 ppm
Dy	1032 ppm
Na	538 ppm
Tb	437 ppm
Er	230 ppm
Yb	123 ppm
Eu	104 ppm
Co	100 ppm
Mn	85 ppm
Lu	35 ppm
Sb	25 ppm
Sc	2 ppm

in high LREE concentrations compared to HREEs. This study shows that the sources of monazite rich alluvial placers in this area have various gneissic and granitoid rocks of the HC of Sri Lanka, especially in the southwest part ([Rupasinghe et al., 1983](#)). Furthermore, the stream sediments in Kalu river, Mahaweli river, and Malwathu Oya may contain high concentrations of REEs and thus detailed studies are recommended by the authors.

Several studies (e.g. [Rupasinghe et al., 1984](#); [Chandrajith, 1999](#); [Rupasinghe et al., 1994](#)) show that the *gem*-bearing alluvial placer deposits (or *gem*-bearing gravels) in Sri Lanka also contain significant concentrations of REEs encouraging further REE prospecting studies.

Heavy minerals, such as zircon, garnet, monazite, ilmenite, magnetite, and rutile were discovered in *gem*-bearing sediments. Based on the studies of [Rupasinghe et al. \(1994\)](#), some minerals act as indicator

Table 10
Relative enrichments (ppm) of REEs in the Sri Lankan gem fields (Source: [Rupasinghe and Dissanayake, 1984](#)) (1–11 indicate sample numbers of the gem fields).

REEs	Ratnapura					Elahera					
	1	2	3	4	5	6	7	8	9	10	11
La	1.41	2.44	1.88	2.6	1.78	1.42	0.95	0.98	1.19	0.93	0.88
Ce	1.9	2.17	1.75	3.47	1.57	1.39	2.23	1.12	1.46	1.1	1
Pr	1.29	1.87	1.46	2.6	1.22	–	0.95	0.93	–	0.87	0.82
Nd	1.36	2.15	1.86	2.38	1.22	1.33	0.85	0.96	1.18	0.89	0.82
Sm	1.44	1.92	1.86	2.42	1.06	1.31	0.87	1	1.04	0.95	0.73
Eu	1.38	1.59	2.02	1.72	0.6	1.43	0.84	1.06	0.87	0.78	0.92
Gd	1.18	1.68	1.95	1.91	0.68	–	–	0.08	0.67	–	–
Tb	0.8	1	1.27	1.31	0.54	0.67	0.5	0.65	0.55	0.59	0.52
Dy	2.23	2.89	3.45	3.89	1.42	–	–	1.05	–	1.36	1.65
Ho	1.06	1.2	1.77	1.5	0.55	–	0.5	0.75	0.54	0.62	0.67
Er	–	–	8.66	10.4	2.71	–	–	4.2	–	3.35	3.97
Tm	–	–	–	–	–	–	–	–	–	–	–
Yb	1.45	1.67	1.94	2.06	0.64	1.08	0.58	1.1	0.68	0.87	0.95
Lu	1.58	1.87	2.09	2.27	0.72	1.2	0.69	1.17	0.76	1.05	0.87

minerals for gems, particularly Mg-rich ilmenite, geikielite, Mg-rich spinel, Ca-rich garnet, and minerals containing REEs, such as davidite and monazite. These indicator minerals of gems have a unique geochemical signature and are enriched in elements, such as REEs, Ta, Nb, Zr, Th, U, Ti, Be, and F ([Dissanayake and Rupasinghe, 1992](#)). The Ratnapura and Walawe Ganga gem fields are abundant in minerals, such as zircon, monazite, rutile, and spinel and the sediment fractions coarser than 63 μm are rich in trace elements, particularly REEs, Zr, Mo, U, Th, and Ta ([Chandrajith, 1999](#)). [Table 9](#) shows certain RE minerals enriched in *gem*-bearing sediments of Sri Lanka.

Although many studies have dealt with the geological and mineralogical aspects of gem deposits in Sri Lanka, only a few addressed the geochemistry of these deposits (e.g. [Rupasinghe et al., 1984](#)). [Rupasinghe and Dissanayake \(1984\)](#) studied the REE abundance in two gem fields, namely, Ratnapura and Elahera of Sri Lanka. According to this study, REEs are enriched in *gem*-bearing sediments of Sri Lanka, particularly LREEs ([Table 10](#)) and the REE concentrations in the Elahera gem field are lower than the Ratnapura gem field.

The discussion in this section highlights that the alluvial placers are enriched in significant concentrations of REEs, and thus those can be regarded as potential REE resources in Sri Lanka. However, more

Table 9
Rare earth minerals in the *gem*-bearing sediments of Sri Lanka (Source: [Dissanayake and Rupasinghe, 1992](#)). SG - specific gravity.

Minerals	SG	Chemical Formula	REEs and other elements
Ekanite	3.28	K(Ca,Na) ₂ Th(Si ₈ O ₂₀)CaTi(O/SiO ₄)	
Serendibite	3.4	(Ca,Mg) ₅ (AlO) ₅ (BO ₃ /(SiO ₄) ₃)	
Anatase	3.9	TiO ₂	Nb, Ta, REEs
Allanite	4	(Ca,Ce)(Fe ³⁺ ,Fe ²⁺)Al ₂ O(SiO ₄)(Si ₂ O ₇)(OH)	
Perovskite	4	CaTiO ₃	Nb, Ta, REEs
Zirkelite	4	(Ca,Ce,Y,Fe)(Ti,Zr,Th) ₃ O ₇	1–14% U ₂ O ₈ , REEs
Rutile	4	TiO ₂	Nb, Ta, Fe
Gadolinite	4 – 4.7	Y ₂ Fe ²⁺ Be ₂ (O/SiO ₄) ₂	
Geikielite	4.05	MgTiO ₃	
Microlite	4.2	(Ca,Na) ₂ (Ta,Nb,Ti) ₂ O ₆ (OH,O,F)	
Zircon	4.3 – 4.5	ZrSiO ₄	U, Th, Hf, REEs
Chromite	4.5 – 4.8	(Fe,Mg)Cr ₂ O ₄	
Ce-Monazite	4.8 – 5	CePO ₄	U, Th, REEs
Columbite	5	(Fe,Mn)(Ta,Nb) ₂ O ₆	
Baddeleyite	5	ZrO ₂	
Tantalite	5 – 8	(Fe,Mn)(Nb,Ta) ₂ O ₆	
Samarskite	5.24	(Y,U,Ca) ₂ (Nb,Fe ²⁺) ₂ (O,OH) ₆	Ta, REEs
Thorite	5.3	ThSiO ₄	U
Fergusonite	5.6 – 5.8	Y(Nb,Ta) ₂ O ₄	4% U ₃ O ₈ , REEs
Scheelite	5.9 – 6.1	CaWO ₄	
Cassiterite	6.8 – 7.1	SnO ₂	Nb, Ta, Ti, Mn, Zr, W, Fe
Thorianite	9.7	(Th,U)O ₂	

Table 11
A summary of REE sources/deposits of Sri Lanka: mineralogy, REE grades and estimated resources. N/A – Not available.

REE prospects/deposits	Host/Source	Mineralogy	REE grades	Estimated resources	References
Eppawala carbonatite	High-grade meta-sedimentary and igneous rocks	Calcite, dolomite, apatite, ilmenite, magnetite, pyrite, magnesite, spinel	~17.84–132.06 ppm	N/A	Pitawala et al., (2003), Manthilake et al. (2008)
Pulmoddai mineral sand deposit	Weathered and eroded hard rocks transported through Mahaweli River, Offshore sediments	Ilmenite, zircon, rutile, monazite, sillimanite	~13413.13–16752.33 ppm	N/A	Amalan et al. (2014), Thilakanayaka (2015), Gamage (2018)
Owala Pegmatite deposit	Formed by post-peak metamorphic, magmatic, hydrothermal activities	Quartz, feldspar, mica, garnet, orthopyroxene, biotite, allanite	~15–20 REE%	N/A	Pitawala et al. (2003, 2008), Fernando et al. (2011), Daily FT (2016)

prospecting studies are recommended to quantify the actual degree of REE enrichment.

5. Discussion

Recently, many countries are involved in REE exploration in various parts of the world, since REEs are considered as the most critical and strategic elements in the world. Although many global REE exploration projects are ongoing, only a few deposits are currently being mined, whereas many are still in the exploration or feasibility stages. Due to the insufficient geological explorations to date, the tonnage and ore grades of many deposits have not been determined. This has been the current status in Sri Lanka and despite having a favourable geological settings for REEs, only a few detailed studies have been carried out to date for the exploration of the Sri Lankan REE resources.

Since the first ever detection of monazite in gem gravels, a few attempts have been made to study the potential of REEs in Sri Lanka (e.g. Wadia and Fernando, 1945a, 1945b; Rupasinghe et al., 1994; Dissanayake et al., 2000). Thus, mineralogy, geochemistry, grade, and tonnage of the discovered REE resources are not explicitly reported. Moreover, there could be unexplored resources in the island terrain, onshore, and offshore with higher REE potentials. In order to serve the national economy, it is crucial to study the identified deposits in detail and explore new resources, including economic feasibility studies.

In this context, Pulmoddai mineral sand deposit has the highest potential for the REE production in Sri Lanka. In 1957, the Ceylon Mineral Sands Corporation was established for the exploitation of the deposit and other beach placer deposits. The Ceylon Mineral Sands Corporation was converted to the Lanka Mineral Sands Ltd as a fully Government-owned company under the Ministry of State Resources and Enterprise Development in 1992. Since the initial establishment of this corporation, the heavy minerals, such as ilmenite, rutile, and zircon separated from the deposit are being directly exported as raw materials without any value addition. This process generates monazite (0.3 wt%) as a by-product along with garnet and this is currently discarded despite the estimated monazite generation of about 300 tonnes per year. However, to date, only a few studies were conducted to quantify the REE content in these beach placer deposits and more importantly, the recovery of REEs from monazite in Sri Lanka was not addressed.

Most of the current REE production in the world is obtained from the carbonatite deposits. For example, Bayan Obo deposit in China, the world's largest REE deposit, has a carbonatite origin. In addition, other major deposits such as Mountain Pass in the USA and Mount Weld in Australia are also associated with carbonatite rocks. Therefore, the occurrence of REE resources with a carbonatite origin seems more likely. A carbonatite deposit is located at Eppawala in the North Central province in Sri Lanka. It was found that the Eppawala carbonatite bedrock along with apatite-bearing regolith are highly enriched in REEs, particularly of LREEs. Therefore, RE metal extraction studies are recommended to explore the full potential of this deposit.

In addition to these two deposits, alluvial placers and pegmatites may also contain high REE concentrations for economic exploitation. Pegmatites could be more favorable due to their relatively high REE concentrations and the added advantage is the ability to extract various industrial metals along with REEs. In this context, pegmatites in Matale district (Fig. 3), especially the deposit in Owala, can be considered as a potential rare earth resource in Sri Lanka. Furthermore, alluvial placer deposits, particularly gem-bearing sediments, also display a great potential to be considered as REE resources. However, more detailed REE prospecting studies should be carried out for these deposits.

Table 11 illustrates the summary of the existing REE sources/deposits of Sri Lanka, including mineralogy, REE grades and estimated resources based on the available data.

6. Conclusions

REEs play a significant role in high-tech and green technologies due to their unique physical and chemical properties. As a result, global demand for REEs is increasing rapidly over the last few decades and expected to rise in the future. Therefore, available REE resources in the world may not be enough to meet the future REE demand. In addition, China currently maintains a monopoly in REE production, and the global stakeholders mainly depend on the Chinese RE supply. This dependency could create supply fluctuations and price manipulations and thus many countries focus their attention on discovering RE resources outside China. This also needs to be recognised in the Sri Lankan mining and minerals industry considering the socio-economic development.

In the global context, carbonatites, alkaline igneous rocks, pegmatites, iron oxide copper-gold (IOCG) deposits, placer deposits, ion-adsorption clays, laterites, and offshore deposits are identified as the major types of REE deposits. However, carbonatites are the primary source of REEs even in the world's largest REE mines, such as Bayan Obo, China and Mountain Pass, USA. In this regard, Eppawala carbonatite in Sri Lanka can be a potential REE resource and according to a few geochemical studies, it contains significant concentrations of LREEs. Moreover, placers are currently considered as a trending source for REEs and those (beach and alluvial) are identified in Sri Lanka. Moreover, Pulmoddai mineral sand deposit is considered as the most potential REE resource in Sri Lanka due to its high monazite enrichment. In addition, pegmatites could also be a potential source for REEs.

Since there are no detailed prospecting studies available for REEs in Sri Lanka beside a few geochemical studies, the authors believe that the gap needs to be addressed to appraise the economic feasibility of the potential resources. In this context, this review could be highly beneficial for the future REE explorations.

CRedit authorship contribution statement

N.M. Batapola: . **N.P. Dushyantha:** . **H.M.R. Premasiri:** Conceptualization, Funding acquisition. **A.M.K.B. Abeysinghe:** Funding acquisition, Resources, Supervision. **L.P.S. Rohitha:** Funding acquisition, Conceptualization. **N.P. Ratnayake:** Funding acquisition, Resources. **D.M.D.O.K. Dissanayake:** Supervision, Resources. **I.M.S.K. Ilankoon:** Funding acquisition, Resources. **P.G.R. Dharmaratne:** Funding acquisition, Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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