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The story of rare earth elements (REEs): Occurrences, global distribution, genesis, geology, mineralogy and global production

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ABSTRACT

Rare earth elements (REEs) including fifteen lanthanides, yttrium and scandium are found in more than 250 minerals, worldwide. REEs are used in various high-tech applications across various industries, such as electrical and electronics, automotive, renewable energy, medical and defence. Therefore, the demand for REEs in the global market is increasing day by day due to the surging demand from various sectors, such as emerging economies, green technology and R&D sectors. Rare earth (RE) deposits are classified on the basis of their genetic associations, mineralogy and form of occurrences. The Bayan Obo, Mountain Pass, Mount Weld and China's ion adsorption clays are the major RE deposits/mines in the world to date and their genesis, chronology and mineralogy are discussed in this review. In addition, there are other RE deposits, which are currently being mined or in the feasibility or exploration stages. Most of the RE resources, production, processing and supply are concentrated in the Asia-Pacific region. In this regard, China holds the dominancy in the RE industry by producing more than 90% of the current rare earth requirements. Thus, REEs are used as a powerful tool by China in trade wars against other countries, especially against USA in 2019. However, overwhelming challenges in conventional RE explorations and mining make secondary RE resources, such as electric and electronic waste (e-waste) and mine tailings as promising resources in the future. Due to the supply risk of REEs and the monopoly of the REEs market, REEs recycling is currently considered as an effective method to alleviate market fluctuations. However, economical and sustainable processing techniques are yet to be established to exploit REEs via recycling. Moreover, there are growing ecological concerns along with social resistance towards the RE industry. To overcome these issues, the RE industry needs to be assessed to maintain long-term social sustainability by fostering the United Nations sustainable development goals (SDGs).

1. Introduction

Rare earth elements (REEs) are governing the modern lifestyle of people, although many people do not aware of the enormous impacts of these elements. However, it has been critical to pay attention to this special group of metals, REEs, due to the important role in modern industrial advancement towards a green economy. REEs were first discovered as a new set of elements at the end of the 18th century in Sweden (Preinfalk and Morteani, 1989; Voncken, 2016). As stated in the International Union of Pure and Applied Chemistry (IUPAC), REEs are a group of seventeen chemical elements, including yttrium (Y), scandium (Sc) and fifteen metallic elements of the lanthanide series (Table 1). Among them, Promethium (Pm) is the only rare earth element, which does not occur naturally (De Lima and Leal Filho, 2015). Due to the similar geochemical behavior of Y and Sc to the lanthanides (Sc only in aqueous medium), they are also considered as REEs (McLennan and Taylor, 2012; Voncken, 2016). These elements are mostly found in trivalent oxidation state, whereas europium (Eu) can also be found in divalent, while cerium (Ce) exhibits tetravalent states (Leybourne et al., 2000; Wang and Liang, 2016).

Generally, atom radii get larger as atomic numbers increase due to the attachment of electrons to the outer shell, however, REEs display decreasing atom radii with the increase of atomic numbers. This phenomenon is known as lanthanide contraction. It occurs when electrons in "*f*" orbitals do not screen the other electrons from the positive pull towards the nucleus. Then, the electrons are pulled towards the nucleus

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Table 1
Description of rare earth elements (REE) (Sources: Taylor and McClennan, 1985; Samson and Wood, 2005; Castor and Hedrick, 2006 and McLemore, 2015). * Promethium does not occur naturally.

Rare Earth Element	Symbol	Oxide	Conversion Factor (% oxide = % element × conversion factor)	Atomic Number	Abundance in the upper crust (ppm)
Scandium	Sc	Sc_2O_3	1.5338	21	14
Yttrium	Y	Y_2O_3	1.269	39	21
Lanthanum	La	La_2O_3	1.173	57	31
Cerium	Ce	Ce_2O_3	1.171	58	63
Praseodymium	Pr	Pr_2O_3	1.17	59	7.1
Neodymium	Nd	Nd_2O_3	1.166	60	27
Promethium	Pm	*	*	61	*
Samarium	Sm	Sm_2O_3	1.16	62	4.7
Europium	Eu	Eu_2O_3	1.158	63	1
Gadolinium	Gd	Gd_2O_3	1.153	64	4
Terbium	Tb	Tb_2O_3	1.151	65	0.7
Dysprosium	Dy	Dy_2O_3	1.148	66	3.9
Holmium	Ho	Ho_2O_3	1.146	67	0.83
Erbium	Er	Er_2O_3	1.143	68	2.3
Thulium	Tm	Tm_2O_3	1.142	69	0.3
Ytterbium	Yb	Yb_2O_3	1.139	70	2.2
Lutetium	Lu	Lu_2O_3	1.137	71	0.31

to reduce the atom radii as atomic number increases (Wang and Schwarz, 1995; Wall, 2014), which allows REEs to show diverse chemical reactivities (Braun et al., 1993; Lee and Byrne, 1993; Braun and Pagel, 1994; Aide and Smith-Aide, 2003).

REEs are often categorised into two sub-groups as light rare earth elements (LREEs) and heavy rare earth elements (HREEs). The elements from ^{57}La to ^{63}Eu are considered as LREEs, whereas the elements from ^{64}Gd to ^{71}Lu, including Y are categorised as HREEs. These two categories of REEs occur in same deposits altogether except Sc. Therefore, Sc is not included any of the above sub-groups. In general, LREEs are more abundant than HREEs (McLemore, 2015).

REEs do not occur as native elements in nature and they are found in the form of minerals, such as phosphates, silicates, carbonates, oxides and halides (Vijayan et al., 1989; Jordens et al., 2013). Earth's crust accounts for 169.1 ppm of total abundance of REEs, including 137.8 ppm of LREEs and 31.3 ppm of HREEs. Therefore, REEs are not as rare as their name suggests. Most of the LREEs have similar abundances in the Earth's crust as much as most industrial metals, such as chromium, nickel, copper, zinc, tin, tungsten or lead (King, 2017). For example, Ce abundance (60–70 ppm, Table 1) is almost similar to the copper abundance in the Earth's crust. Therefore, in this context, the word 'rare' essentially implies that REEs are not commonly concentrated as economic ore deposits, though the viable deposits are distributed across the world in relatively low concentrations (Haxel et al., 2002).

2. REE applications

In the 1890s, lanthanum oxide was used in a commercialised gas mantle in Vienna as the first reported REE application (Neary and Highley, 1984; Szabadváry, 1988). Ever since, the application of REEs has become crucial in different industrial sectors, especially in green energy and military sectors. Table 2 contains prominent applications of REEs in various sectors. These elements are currently used in different chemical forms, such as metals, alloys, oxides and chlorides. Usage of Pr, Nd, Gd, Dy and Tb in permanent magnets is considered as the dominant REE application. La and Ce are used as stabilizers in catalytic compounds, which claims the second-highest usage of REEs (Koerth-Baker, 2012; Mancheri et al., 2019a). Therefore, modern society has been significantly depending on large quantities of REEs due to their unique physical and chemical properties, such as high thermal stability, high electric conductivity, strong magnetism and high luster. Besides, due to the optical properties, namely, fluorescence in REEs, they can emit light in the visible range. Therefore, REEs are used in high efficiency lighting phosphors in compact fluorescent bulbs (CFLs) and light-emitting diode bulbs (LEDs) (Machacek et al., 2015). Eu, the most prominent example, has turned into a highly demanded REE in last half of the 20th century, since it was used as a colour-producing phosphor in video screens along with Tb and Y (Mertzman, 2019). The usage of REEs in modern technology has reduced the requirement of other materials and increased efficiency at a higher rate. Therefore, REEs are defined as "The Vitamins of Modern Industry" (Balaram, 2019). Table 3 shows the specific REE requirements in some applications.

2.1. Role of REEs in green energy applications

The world's energy requirements have been steadily increasing for the last few decades and most of the energy demands are fulfilled by the fossil-fuel-based energy sources, such as oil, coal and natural gas. As a result, consequences such as air pollution, global warming and climate change have become overwhelming concerns in the present world. Furthermore, impending issues, such as oil price volatility, geopolitical concerns, economic vulnerability and peak oil have already created a necessity to diversify the energy portfolios towards a global green energy system (Stegen, 2015). Therefore, renewable energy sources like solar, wind and tidal power have drawn global attention to meet future energy demands. In this regard, due to the aforementioned superior characteristics of REEs, especially HREEs play a key role in high-technology and environmentally friendly energy harvesting techniques, for instance, solar panels and wind-power turbines (Judge et al., 2017).

2.1.1. Solar cells

Solar power is a green energy source, which can be used for sustainable energy production as an alternative for hydrocarbon energy sources. Solar power is captured and converted into electricity by solar cells/photovoltaic cells. During this conversion, solar cells do not absorb very low energy photons, though very high energy photons are efficiently absorbed. This phenomenon is known as the spectral mismatch and it is the main energy loss in the process (Strümpel et al., 2007; Van Der Ende et al., 2009). Since REE trivalent ions are able to convert photons into different wavelengths due to their unique '4*f*' electron configuration, they are used to merge two very low energy photons into one high energy photon as well as to split very high energy photon into two lower energy photons. These processes are called as upconversion and downconversion, respectively (Andrews, 2008; Goldschmidt and Fischer, 2015). Solar cells are able to absorb more photons after the upconversion and downconversion and reduce the energy losses in the conversion. Therefore, REE ions, such as Pr^{3+}, Gd^{3+}, Eu^{3+} and Er^{3+} are used as nanoparticle-based materials to enhance the power conversion efficiencies (relative increase by 1.34%) in

Table 2
Industrial applications of REEs (Source: Balaram, 2019).

Area	Applications
Electronics	Television screens, computers, cell phones, silicon chips, monitor displays, long-life rechargeable batteries, camera lenses, light emitting diodes (LEDs), compact fluorescent lamps (CFLs), baggage scanners, marine propulsion systems.
Manufacturing	High strength magnets, metal alloys, stress gauges, ceramic pigments, colorants in glassware, chemical oxidizing agent, polishing powders, plastics creation, as additives for strengthening other metals, automotive catalytic converters.
Medical Science	Portable X-ray machines, X-ray tubes, magnetic resonance imagery (MRI) contrast agents, nuclear medicine imaging, cancer treatment applications, and for genetic screening tests, medical and dental lasers.
Technology	Lasers, optical glass, fiber optics, masers, radar detection devices, nuclear fuel rods, mercury-vapor lamps, highly reflective glass, computer memory, nuclear batteries, high temperature superconductors.
Renewable Energy	Hybrid automobiles, wind turbines, next generation rechargeable batteries, biofuel catalysts.
Others	The europium is being used as a way to identify legitimate bills for the Euro bill supply and to dissuade counterfeiting. An estimated 1 kg of REE can be found inside a typical hybrid automobile. Holmium has the highest magnetic strength of any element and is used to create extremely powerful magnets. This application can reduce the weight of many motors.

solar cells (Yu et al., 2019; Zhang et al., 2019).

2.1.2. Wind turbines

Wind energy is a fast-growing green energy source, which is used to generate electricity via wind turbines. In this process, the kinetic energy of the wind is converted to mechanical energy by wind turbines to power a synchronous electric generator. Since REEs show strong magnetism, 100 g of RE permanent magnet can produce the same magnetic field produced by 1 kg of non-rare earth permanent magnet (Athurupane, 2014). Therefore, powerful permanent magnets containing REEs, such as Nd and Dy are employed in synchronous generators in direct-drive wind turbines (Heier, 2014). These magnets allow more lightweight designs and compacted direct-drive wind turbines compared to the gearbox wind turbines (Dodd, 2018). Therefore, direct-drive wind turbines offer more advantages, such as low turbine downtime, high reliability and less maintenances over gearbox turbines. As a result, direct-drive turbines have been effective and more preferable even for offshore wind farms and sites with low wind speed (Polinder et al., 2006; Ribrant and Bertling, 2007; Morris, 2011). However, due to the turbulences in REE supply in the market, many companies and governments have already developed alternative REE free generators for wind turbines using new materials with similar functionality (Pavel et al., 2017).

2.2. Role of REEs in agricultural applications

REEs have been used in zootechnical and agricultural applications, as they are essential in functional and structural molecules in biological systems (Abdelnour et al., 2019). In this context, REEs are used as feeding additives to enhance growing and fattening of farming animals, such as pigs, chicken, cattle, fish, ducks and rabbits. This REE application is also beneficial to increase the milk productions of dairy cows, survival rates of fish and egg production of laying hens (He et al., 2001; Redling, 2006). Moreover, REEs are beneficial elements to plants and thus have been used in fertilizers in soluble forms at low concentration in China since 1972 (Baisheng, 1985). Crops absorb soluble REE ions like other cations and accumulate in plant tissues. This REE accumulation causes positive agronomic effects, such as quality and yield improvements of various kinds of crops (Buckingham et al., 1999; Pang et al., 2002). Although applied REEs could enter the human body via food chains, it is supposed that the REE concentration is low (i.e. 12 to 120 mg per day) and thus adverse effects are not yet reported (Baisheng, 1985; Ramos et al., 2016).

2.3. Role of REEs in military applications

REEs have also considered as strategic elements due to their advanced military applications. Permanent magnets such as samarium cobalt (SmCo) and neodymium iron boron (NdFeB) magnets are highly used in many defence applications, such as tomahawk cruise missiles, smart bombs, joint direct attack munitions, joint air and ground fin actuators and predator unmanned aircrafts. SmCo magnets are capable of retaining high magnetic strength even at a higher temperature. Therefore, SmCo magnets are significantly used in precision-guided missiles, smart bombs and aircrafts. Since NdFeB magnets show the strongest magnetic strength, they are used in small quantities to produce lighter magnets in military weapons system (Humphries, 2010; Grasso, 2013). Moreover, REEs are used for energy storages, density amplifications and capacitance in electronic warfare and directed energy weapons. In addition, REEs like Y, Eu and Tb are used in energy and resolution amplifiers in targeting applications, such as in night-vision goggles and laser weapons (Preinfalk and Morteani, 1989; Meyer and Bras, 2011; Massari and Ruberti, 2013).

3. Rare earth (RE) occurrences and global distribution

Rare earth (RE) deposits are also formed via primary and secondary processes (i.e. two geological processes). Primary processes consist of

Table 3
REE requirements by application (Sources: Long et al., 2012; Jordens et al., 2013).

REE application	La%	Ce%	Pr%	Nd%	Sm%	Eu%	Gd%	Tb%	Dy%	Y%	Others%
Magnets	–	–	23.4	69.4	–	–	2	0.2	5	–	–
Battery alloys	50	33.4	3.3	10	3.3	–	–	–	–	–	–
Metal alloys	26	52	5.5	16.5	–	–	–	–	–	–	–
Auto catalysts	5	90	2	3	–	–	–	–	–	–	–
Petroleum refining	90	10	–	–	–	–	–	–	–	–	–
Polishing compounds	31.5	65	3.5	–	–	–	–	–	–	–	–
Glass additives	24	66	1	3	–	–	–	–	–	2	4
Phosphors	8.5	11	–	–	–	4.9	1.8	4.6	–	69.2	–
Ceramics	17	12	6	12	–	–	–	–	–	53	–
Other	19	39	4	15	2	–	1	–	–	19	–

*Percentages are estimated from the total REE content required in a given application.

Table 4
RE resources and their global distribution (Source: Voncken, 2016).

Deposit	Location	Type	Main REEs	REE-mineral(s)
Bayan Obo	China	Carbonatite/hydrothermal	La, Ce, Nd	bastnasite, parasite, monazite
Mountain Pass	USA	Carbonatite	LREE	bastnasite
Mount Weld	Australia	Laterite/Carbonatite	LREE	apatite, monazite, synchysite, churchite
Illimaussaq	Denmark	Peralkaline igneous	La, Ce, Nd, HREE	eudialyte, steenstrupine
Pilanesberg	South Africa	Peralkaline igneous	Ce, La	eudialyte
Steenkampskraal	South Africa	Vein	La, Ce, Nd	monazite, apatite
Hoidas Lake	Canada	Vein	La, Ce, Pr, Nd	apatite, allanite
Thor Lake	Canada	Alkaline igneous	La, Ce, Pr, Nd, HREE	bastnasite
Strange Lake and Misery Lake	Canada	Alkaline igneous/hydrothermal	La, Ce, Nd, HREE	gadolinite, bastnasite
Nolans Bore	Australia	Vein	La, Ce, Nd	apatite, allanite
Norra Kärr	Sweden	Peralkaline igneous	La, Ce, Nd, HREE	eudialyte
Khibina and Lovenzero	Russia	Peralkaline igneous	LREE + Y, minor HREE	eudialyte, Apatite
Nkwombwa Hill	Zambia	Carbonatite	LREE	monazite, bastnasite
Kagankunde	Malawi	Carbonatite	LREE	monazite-Ce, bastnaesite-Ce
Tundulu	Malawi	Carbonatite	LREE	synchesite, parasite, bastnasite
Songwe	Malawi	Carbonatite	LREE, Nd	synchesite, apatite
Chinese ion adsorption deposits	China	Soils	La, Nd, HREE	clay minerals
Maoniuping	China	Carbonatite	LREE	bastnasite
Dong Pao	Vietnam	Carbonatite	LREE	bastnasite, parisite

magmatic, hydrothermal and/or metamorphic processes, though secondary processes imply weathering and sedimentary transport (Mitchell, 2015; Zhou, 2017). In this regard, RE deposits can be categorised into primary and secondary deposits. Primary deposits are commonly associated with carbonatites and alkaline-peralkaline igneous rocks, whereas secondary deposits, such as placer and ion adsorption deposits (e.g. China), are formed due to the erosion and weathering of primary deposits (Goodenough et al., 2016; Zhou, 2017). Beside this classification scheme of RE deposits, they can be further classified on the basis of their genetic associations, mineralogy and form of occurrences (Balaram, 2019).

About 34 countries have been identified with RE deposits and Table 4 shows the RE resources distribution in the world (Chen, 2011). According to the United States Geological Survey (USGS) Mineral Commodity Summaries 2016, worldwide RE reserve estimation was 130 million tonnes and China and Brazil have 42.3% and 16.9% of these reserves, respectively (United States Geological Survey (USGS), 2016). The majority of REEs are found in carbonatite deposits, where LREEs are typically enriched. Fig. 1 shows the global carbonatite distribution. Alkaline-peralkaline igneous rocks also comprise of significant REE concentrations, where HREEs are often enriched.

3.1. Rare earth (RE) minerals

More than 250 REE-bearing minerals have been identified to date in various mineral classes, such as carbonates, phosphates, silicates, oxides and halides (Vijayan et al., 1989; Chi et al., 2001; Gupta and Krishnamurthy, 2005). Generally, LREEs are concentrated in carbonates and phosphates, whereas HREEs are concentrated in oxides and a part of phosphates (Kanazawa and Kamitani, 2006). Bastnaesite and monazite are the most common RE minerals found in RE deposits. Therefore, most of the global RE production is provided via bastnaesite and monazite along with xenotime (Haque et al., 2014; Zhou, 2017). Table 5 indicates primary REE minerals and their formulae.

3.1.1. Bastnaesite

The largest percentage of world's economic RE resources is considered as the bastnaesite deposits distributed in China and the USA. Bastnaesite does not contain U or Th and it is considered as the primary source of LREEs (Table 5). This mineral contains approximately 70% of REOs (Jordens et al., 2013; Voncken, 2016). Bastnaesite is often found in geological environments, such as vein deposits, contact metamorphic zones and pegmatites. In addition, it occurs in carbonate – silicate rocks with alkaline intrusive, quartz veins, fluorite – bearing veins and breccia fillings in Permian sandstone (Gupta and Krishnamurthy, 2005).

3.1.2. Monazite

The second largest segment is the monazite deposits distributed in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand and USA. Monazite is a widespread RE mineral, which commonly occurs in beach sands. However, it also occurs in granite, gneiss and other igneous and metamorphic rocks as an accessory mineral (Wall, 2014). In addition, it can be found in complex ores together with iron oxides, aluminosilicates and apatite (Ferron et al., 1991). Monazite is usually associated with heavy minerals, such as ilmenite, magnetite, rutile and zircon due to its high specific gravity and resistance to chemical weathering (Long et al., 2012).

This mineral generally contains 10–40% La_2O_3, 4–12% ThO_2, 20–30% Ce_2O_3 and high amount of Nd, Pr and Sm (Gupta and Krishnamurthy, 2005; Thompson et al., 2012). It is considered as a major source of cerium and LREEs (Fernando, 1986; Voncken, 2016; Xaba et al., 2018). REO content in monazite is approximately 70% (i.e. similar to bastnaesite). However, unlike bastnaesite, monazite contains thorium and uranium (Trifonov, 1963; Cesbron, 1989; Ferron et al., 1991; Gupta and Krishnamurthy, 2005). Monazite in placer deposits contains a higher amount of thorium and uranium than monazite from carbonatite deposits. The estimated inland monazite placer deposit tonnage was 10.21 million tonnes in 2005, in which China, USA and India possess 36%, 13% and 3%, respectively (Pandey, 2011). Table 6 presents the potential monazite sources in the world.

3.1.3. Other RE minerals

The rest of the resources constitute xenotime, allanite, euxenite, apatite, cheralite, eudialyte, loparite (Table 5), phosphorites, rare earth bearing (ion absorption) clays, secondary monazite and spent uranium solutions. Xenotime is an yttrium phosphate mineral with 67% of REO content, mostly containing HREEs (Gupta and Krishnamurthy, 2005). Allanite is commonly occurred as an accessory mineral in igneous rocks, such as granites, syenites, diorites and associated pegmatites. However, it is rarely enriched of concentrations enough to form an ore of REEs. Euxenite is a common oxide mineral which generally occurs in granite pegmatites associated with quartz, feldspars, ferrocolumbite, ferrotantalite and monazite (Long et al., 2012).

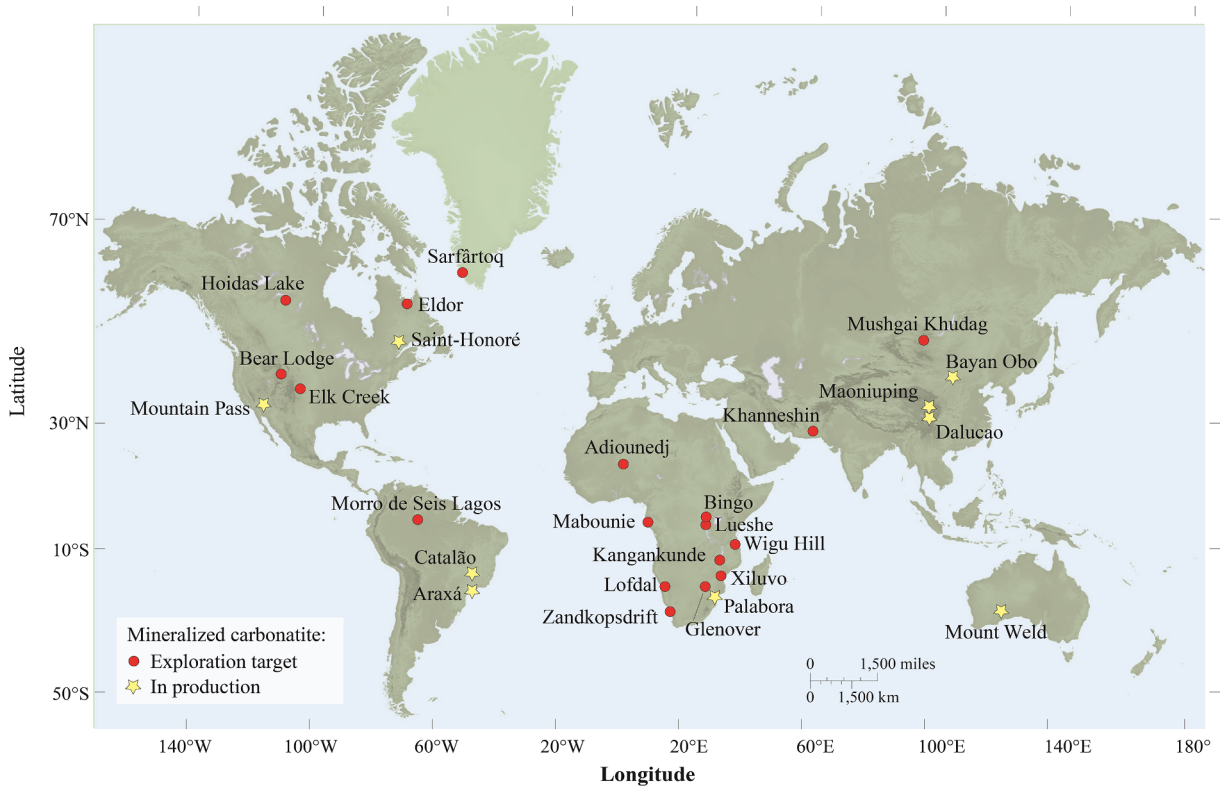

Fig. 1. Global carbonatite distribution including deposit in production and exploration targets (Sources: Eggert et al., 2016; Verplanck et al., 2016).

Table 5
Primary REE-bearing minerals and their formulae (Source: Dostal, 2017).

Mineral	Formula
Allanite	$(Y,La,Ca)_2(Al,Fe^{3+})_3(SiO_4)_3(OH)$
Apatite	$(Ca,La)_5(PO_4)_3(F,Cl,OH)$
Bastnaesite	$(La,Y)\ (CO_3)F$
Eudialyte	$Na_4(Ca,La)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$
Fergusonite	$(La,Y)NbO_4$
Gittinsite	$CaZrSi_2O_7$
Limoriite	$Y_2(SiO_4)(CO_3)$
Kainosite	$Ca_2(Y,La)_2Si_4O_{12}(CO_3).H_2O$
Loparite	$(La,Na,Ca)(Ti,Nb)O_3$
Monazite	$(La,Th)PO_4$
Mosandrite	$(Na,Ca)_3Ca_3La\ (Ti,Nb,Zr)(Si_2O_7)_2(O,OH,F)_4$
Parisite	$Ca(La)_2(CO3)_3F_2$
Pyrochlore	$(Ca,Na,La)_2Nb_2O_6(OH,F)$
Rinkite (Rinkolite)	$(Ca,La)_4Na(Na,Ca)_2Ti(Si_2O_7)_2(O,F)_2$
Steenstrupine	$Na_{14}La_6Mn_2Fe_2(Zr,Th)(Si_6O_{18})_2(PO_4)_7{\cdot}3H_2O$
Synchysite	$Ca(La)(CO_3)_2F$
Xenotime	YPO_4
Zircon	$(Zr,La)SiO_4$

3.2. Major RE deposits in the world

3.2.1. Bayan Obo deposit

The Bayan Obo deposit is considered as the world's biggest RE deposit and it was discovered as an iron deposit (REE-Nb-Fe) in 1927 (Fan et al., 2016). This deposit is located in Inner Mongolia (at the north margin of the North China Craton) bordering an early Paleozoic active continental margin to the north (Xiao andKusky, 2009). The Bayan Obo deposit is hosted by the Bayan Obo group, which was traditionally divided into nine lithological units; named as H1 to H9 in the ascending order. All units are mainly comprised of meta-sandstones and slates except for H8. The H8 predominantly consists of dolomitic marbles with both fine- and coarse-grained varieties and it is the host rock for the majority of ores (Chao et al., 1992). Therefore, dolomite is considered as the host for most RE ores, which extends 18 km from east to west with an approximate width of 2 km. However, different types of carbonatite dikes are widely distributed with an intrusive sequence of dolomite (ferroan) type, dolomite-calcite (magnesian) type, and calcite (calcic) type (Yang et al., 2011a,b). Due to the wide distribution of carbonatite dikes in the Bayan Obo deposit, genesis of RE ores have been deduced to be associated with carbonatite. According to Liu et al. (2018), the Bayan Obo deposit is formed by the Mesoproterozoic carbonatite magmatism, followed by the Paleozoic hydrothermal dolomitization. Liu et al. (2018) also reported that REEs were re-fertilized during the Paleozoic hydrothermal dolomitization. Moreover, different models of ore genesis, such as syngenetic sedimentary deposition (Meng, 1982), metasomatism associated with granitic magmatism (Wang, 1973), and deposition from exhalative, probably carbonatite related, hydrothermal fluids (Zhongxin et al., 1992) have been proposed for the Bayan Obo deposit (Fan et al., 2016). However, the genesis of this deposit still remains a subject of debate mainly due to immense post-ore magmatic and hydrothermal modifications (Smith et al., 2015; Hu et al., 2019). Furthermore, ore bodies in the Bayan Obo deposit have complex geochronology. Smith et al. (2016) reported that the age of carbonatites in the Bayan Obo deposit is about 1230–1350 Ma (million years) and about 400–450 Ma based on Sm-Nd mineral isochrones and Th-Pb mineral isochrones, respectively. Both periods have also been identified from core to rim U-Pb isotope variation in zircon (Campbell et al., 2014). This has supported interpretations of multistage mineralisation, metamorphism and metasomatic overprint of the ores (Smith et al., 2015). The variation of elemental composition in different types of carbonatites is crucial for understanding the genesis of RE mineralization. The RE concentrations in the Bayan Obo deposit thus differ according to the type of carbonatite dike. For example, the calcite type carbonatite dikes have higher RE concentrations over others (Yang et al., 2019).

The Bayan Obo deposit contains RE reserves (non-Joint Ore Reserves Committee (JORC) compliant) of over 57.4 million tonnes, niobium (Nb) reserves of 2.16 million tonnes and iron (Fe) reserves of

Table 6
Primary monazite mineral sources and their rare earth contents (percentage of total rare-earth oxide) (Sources: Hedrick, 1999; Kumari et al., 2015).

Rare earth elements	Monazite					
	North Capel, West Australia	North Stradbroke Island, Queensland, Australia	Green Cove Springs, USA	Nangang, Guangdong, China	East Coast, Brazil	Mount Weld, Australia
Cerium	46.0	45.8	43.7	42.7	47.0	51.0
Lanthanum	23.9	21.5	17.5	23.0	24.0	26.0
Neodymium	17.4	18.6	17.5	17.0	18.5	15.0
Praseodymium	5.0	5.3	5.0	4.1	4.5	4.0
Samarium	2.5	3.1	4.9	3.0	3.0	1.8
Europium	0.1	0.8	0.2	0.1	0.1	0.4
Gadolinium	1.5	1.8	6.6	2.0	1.0	1.0
Terbium	0.0	0.3	0.3	0.7	0.1	0.1
Dysprosium	0.7	0.6	0.9	0.8	0.4	0.2
Erbium	0.2	0.2	Trace	0.3	0.1	0.2
Yttrium	2.4	2.5	3.2	2.4	1.4	Trace
Holmium	0.1	0.1	0.1	0.1	Trace	0.1
Thulium	Trace	Trace	Trace	Trace	Trace	Trace
Ytterbium	0.1	0.1	0.2	2.4	0.0	0.1
Lutetium	Trace	0.0	Trace	0.1	ND	Trace
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0

ND – not detected.

minimum 1500 million tonnes having respective average grades of 6% REOs, 0.13% Nb_2O_5 and 35% iron oxide (Fan et al., 2014). This deposit is rich in LREEs (Table 4) and those account for 97% of total REEs of the deposit (Su, 2009; Yang et al., 2013). In the Bayan Obo deposit, four types of REE mineralizations are identified based on their relationship with the occurrences of rocks or veins. They are carbonatite dyke, ore-hosting dolomite marble, banded REE-Nb-Fe ore, and late-stage REE vein (Fan et al., 2016). However, the geochronology of these mineralization has been highly debated due to the different results of mineralization ages obtained by various dating methods, such as U-Th-Pb, Sm-Nd, Rb-Sr, K-Ar, Ar-Ar, Re-Os, and La-Ba. Nevertheless, there are three main opinions on mineralization ages, including Mesoproterozoic mineralization (Fan et al., 2014; Yang et al., 2011b), Early Paleozoic mineralization (Hu et al., 2009), and Two-stage mineralization (Campbell et al., 2014; Zhu et al., 2015). The Bayan Obo deposit constitutes approximately 162 minerals along with more than 20 REE-bearing minerals and 15 niobium minerals. The earliest formed REE-bearing mineral was monazite-(Ce) and it was subsequently overprinted by bastnaesite-(Ce). Afterwards, bastnaesite was again overprinted by different Ca-REE fluorocarbonates, such as parisite (Table 5) (Smith et al., 2015). Currently, three types of apatites and four types of monazites have been identified in the Bayan Obo deposit and they are presented in Table 7.

Since the apatites have different textures and REE contents, REE mineralization in this deposit was not derived from a single event. Type 1 apatite has high REE and Sr contents, implying that it is of carbonatite origin, whereas other RE minerals have been derived by remobilization and recrystallization of the original RE minerals (Deng et al., 2017; Ren et al., 2019).

In the Bayan Obo deposit, open-pit mining is employed for the mining of RE ores. The Main Ore Body, the East Ore Body and the West Ore Body are the three main ore zones in this deposit and the Main and the East ore bodies are currently being actively exploited (Kanazawa and Kamitani, 2006). In 2005, the production of this deposit was 55,300 tonnes of REOs, which accounted for 47% and 45% of the total RE production in China and the world, respectively (Wu, 2008).

3.2.2. Mountain Pass deposit

The Mountain Pass deposit in California, USA is the second largest RE deposit in the world, discovered in 1949 and operations began in 1952. This deposit is situated in the central Mojave Desert of California that is 75 km SupplySide West (SSW) of Las Vegas, Nevada. The Mountain Pass district is mainly underlain by autochthonous,

Table 7
Types of apatites and monazites based on textural features (Source: Deng et al., 2017).

Types of RE minerals	Remarks
Apatite	
Type 1	Associated with Type 1 monazite.
Type 2	Present in the form of clusters of assemblages in which bastnaesite and parisite occur at the rim.
Type 3	Occurs with fluorite and bastnaesite veinlets as linear arrays.
Monazite	
Type 1	Occurs at the border of Type 1 apatite grains.
Type 2	Present as clusters intergrowing with parisite and fluorite.
Type 3	Type 3 and Type 4 monazites occur as polymineralic and monomineralic veinlets, respectively.
Type 4	

Proterozoic crystalline basement rocks (Yang et al., 2019). The parent rock of this RE ore deposit is a Sulphide Queen Carbonatite which is associated with ultrapotassic alkaline rocks vary from shonkinite, through syenite to granite. Therefore, this carbonatite is concerned as unusual comparing to other RE mineralized carbonatites (Castor, 2008). Due to field relationships and similar enrichment of elements, such as strontium (Sr), barium (Ba) and LREEs in these rocks, many previous studies have inferred that carbonatite magma was derived from the same source as the ultrapotassic suite and it was ultimately derived from mantle enriched by either metasomatism, or contamination by subducted crustal rocks (Castor, 2008). However, the age of carbonatites in the Mountain Pass deposit is reported as 1375 ± 5 Ma which is 25 Ma younger than that of ultrapotassic rocks (DeWitt, 1987). Therefore, this apparent age difference is not compatible with the above hypothesis that carbonatite and ultrapotassic rocks have been derived from the same parental magma that was simultaneously melted. Thus, the petrogenesis of the carbonatite in the Mountain Pass deposit still being highly debated (Haxel, 2005; Poletti et al., 2016). Moreover, the carbonatite dykes and fluorite veins are surrounded by a zone of fenitization which is considered as an alteration occurred by alkali metasomatism at the contact of the carbonatite intrusive complex (Smith

et al., 2016).

Bastnaesite-(Ce) is the major RE mineral found in the Mountain Pass deposit, and parisite-(Ce) and monazite-(Ce) are present as minor RE minerals (Smith et al., 2016). This deposit has an ore grade of 8.5% of REOs particularly with extreme LREE enrichment. Moreover, high Ba enrichments are shown in this deposit and however, Nb and P are depleted (Castor, 2008; Smith et al., 2016; Zhou et al., 2016).

From 1960s to mid-1990s, this deposit was known as the largest LREE resource in the world as it is significantly enriched by LREEs (Table 4) despite the Nd depletion. Due to the wastewater pipeline leakages to the environment, REE operations were suspended in 1998, and consequently, mining operations and RE production of this sole domestic producer were ceased in 2002 (Koltun and Tharumarajah, 2014). Since the deposit has the potential of producing around 19 thousand tonnes of REOs per year, Molycorp acquired this deposit in 2008 and it was subsequently reopened in 2012. However, due to the bankruptcy of Molycorp and the low prices of REEs in China, the operations were terminated again in 2015. Nevertheless, due to the ongoing trade disputes between the USA and China, rare earth mining activities have been reconsidered and will be restarted by the end of 2020 to extract RE concentrates and oxides, such as La, Ce, Nd and Y (Eric, 2019a).

3.2.3. Mount Weld deposit

The Mount Weld deposit in Western Australia is considered to be one of the richest RE deposits in the world and it is found in a 70–130 m thick lateritic profile over an alkaline carbonatite complex (Hoatson et al., 2011). Moreover, there are significant RE concentrations in the lacustrine sediments which is developed on the lateritic profile. Beside RE resources, this acts as the host to many significant resources, such as Nb, Ta, Zr and phosphate (Smith et al., 2016). This carbonatite intrusion follows a sequence of Archaean volcano-sedimentary within the fault bounded Laverton tectonic zone and it is metamorphized under greenschist facies. The age of the primary carbonatite intrusion is reported as 2080–2100 Ma, whereas the age of the lateritic profile is unknown. However, it has been recorded that the lacustrine sediments which overlies the lateritic profile belongs to the age of late Cretaceous to early Cainozoic. According to isotropic constraints, the primary carbonatite in the Mount Weld deposit was derived from melting of an enriched mantle source. The Mount Weld deposit consists of Palaeoproterozoic alkaline magmatic province which includes kimberlites and other carbonatites (Willett et al., 1986; Hoatson et al., 2011; Jaireth et al., 2014). The lateritic regolith is concerned as the host to main economic RE resources. The long term leaching and redeposition of REEs by groundwater during the Mesozoic and Cainozoic ages has significantly contributed the RE enrichment of this deposit and thus formed an economic resource (Smith et al., 2016).

The Mount Weld deposit has a secondary RE phosphate mineralogy and these phosphates, mostly monazite, are contained in iron oxide minerals (Haque et al., 2014). The carbonatite bed rock is comprised of RE minerals, such as apatite, monazite-(Ce) and synchysite, whereas the lateritic profile contains neoformed apatite and monazite-(Ce), crandallite, goyazite, gorceixite and florencite-(Ce) which were formed by weathering and redeposition of carbonatite and other RE minerals. In addition, certain parts of the deposit constitute distinct xenotime and churchite mineralogy, resulting in significant HREE concentrations (about 3% of heavy REOs) in the deposit (Hoatson et al., 2011; Haque et al., 2014). This deposit has the capacity of producing more than 26 thousand tonnes REOs per annum over more than 25 years. The Mount Weld consists of four deposits, namely, the Central Lanthanide Deposit (CLD - one of the highest grade REE deposits in the world), Duncan, Crown and Swan (Lynas, 2015).

3.2.4. Ion adsorption clay deposits in Southern China

Ion adsorption deposits are another type of unique RE deposits typically found in Southern China as weathered-crust elution-deposits with HREE enrichments (Table 4) (Li and Yang, 2014; Voncken, 2016). Since unique geological conditions are required to form ion adsorption RE deposits, these deposits are only found in certain parts of Southeast Asia to date, in addition to the deposits in Southern China (Takeda and Okabe, 2014). These deposits were first discovered in 1970 in Ganzhou, China. These ion adsorption clays contain 0.02 – 1% of REOs and account for 2.9% of China's total RE reserves (Su, 2009). Therefore, 26% of China's total RE production was originated from these deposits during the period of 1988–2008, and since 2009, it has been reached up to 35% (Su, 2009).

These clay deposits are formed through a process of REE leaching from granite, granite porphyry or even gneisses by groundwater under high temperature and humidity where RE minerals are dissolved in groundwater. During the penetration and migration processes, the produced REE ions are weakly adsorbed onto the surface of the clay-rich thick soil layer developed above the granite bedrock (Van Gosen et al., 2014; Estrade et al., 2019). Some of the adsorbed REEs can be easily extracted from the clay by ion exchange (Wall, 2014; Deng et al., 2019). Therefore, extraction of REEs from these clay deposits is economically viable due to the easy extractability, despite their low concentrations. In addition, radioactive elements in clay deposits are depleted away during the weathering, and as a result, the adverse effects of radioactive contaminants in these deposits are minimized.

Table 8 presents the REE contents of major RE deposits, including

Table 8
REO% in Bayan Obo, Mountain Pass and ion adsorption clay deposits (Sources: Gupta and Krishnamurthy, 2005; Schüler et al., 2011; Shi, 2009).

Ore	Bayan Obo		Mountain Pass	Ion adsorption clays					
REOs	Bastnaesite	Monazite	Basnasite	*Site A	*Site B	*Site C	*Site D	*Site E	*Site F
La_2O_3	27	23.4	33.2	2.1	20	8.5	29.8	27.4	13.1
CeO_3	50	45.7	49.1	12.8	1.3	1.1	7.2	3.1	1.3
Pr_6O_{11}	5	4.2	4.3	1.1	5.5	1.9	7.4	5.8	4.9
Nd_2O_3	15	15.7	12	5.1	26	7.4	30.2	18.7	13.4
Sm_2O_3	1.1	3.1	0.8	3.2	4.5	2.6	6.3	4.3	4
Eu_2O_3	0.2	0.1	0.1	< 0.3	1.1	0.2	0.5	< 0.3	0.2
Y_2O_3	0.3	3.1	0.1	62.9	25.9	49.9	10.1	26.4	41.7
Gd_2O_3	0.4	2	0.2	5.7	4.5	6.8	4.2	4.4	5.1
Tb_2O_3	Trace	0.1	0.02	1.1	0.6	1.4	0.5	0.7	1.2
Dy_2O_3	Trace	1	0.03	7.5	4.1	8.6	1.8	4	7.1
Ho_2O_3	Trace	0.1	< 0.01	1.6	< 0.3	1.4	0.3	0.5	1.1
Er_2O_3	1	0.5	< 0.01	4.3	2.2	4.2	0.9	2.3	3.1
Tm_2O_3	Trace	0.5	< 0.01	0.6	< 0.3	1.2	0.1	0.3	1.5
Yb_2O_3	Trace	0.5	< 0.01	3.3	1.4	4.1	0.6	2	2
Lu_2O_3	Trace	0.1	< 0.01	0.5	< 0.3	0.7	0.1	< 0.3	0.5

*Sites A to F represent six provinces in southern China.

Bayan Obo, Mountain Pass and ion adsorption clays.

3.3. Other RE deposits

In addition to the above-mentioned prominent RE deposits, there are many other RE deposits which are currently being mined or having potential economic RE concentrations. The Lovozero deposit on the Kola Penisula in Russia is considered as the World's largest layered peralkaline syenite intrusion and mining operations were started since 1951 for Nb and REEs (Wall, 2014; Zartman and Kogarko, 2017). However, the underground mine at Karnarsurt is the only active mine in the deposit, which is currently operated by Lovozerskiy Gok (Smith et al., 2016). RE mineralization of the Lovozero deposit is dominated by loparite-(Ce) along with RE minerals, such as steenstrupine-(Ce), vuonnemite, nordite-(Ce), vitusite-(Ce), mosandrite, monazite-(Ce) and cerite (Kogarko et al., 2002).

Another RE deposit which is currently in the production stage is the Maoniuping deposit in the eastern Tibetan Plateau. It is the second largest carbonatite-related REE deposit (CARD) in China. This deposit is hosted by a carbonatite-syenite complex which consists of two sections; namely Guangtoushan and Dagudao (Zheng and Liu, 2019). This carbonatite-syenite complex is located in the Cenozoic Mianning-Dechang (MD) REE belt. The India-Asia continental collision, 65–26 Ma ago, resulted in this MD REE belt which was formed by magmatism along with torsional and shear deformations (Hou et al., 2006). This deposit was formed approximately 25 Ma ago through melting of subcontinental lithospheric mantle which had been subjected to the metasomatism by high fluxes of REE- and CO_2-rich fluids derived from subducted marine sediments (Hou et al., 2015). The total estimated reserves of the Maoniuping deposit is 3.17 million tonnes and it is typically enriched of LREEs (Zheng and Liu, 2019). Furthermore, the Weishan Lake deposit located in Shandong, China, the carbonatite-associated REE deposits (CARDs), is currently being mined. The total reserves of REEs in this deposit is estimated to be about 2.55 million tonnes with an average grade of 3.13% REOs. Main REE-bearing minerals in this deposit are bastnaesite and parisite along with several associated minerals, such as barite, calcite, quartz and fluorite (Li and Yang, 2016).

In addition to the RE deposits which are in production, many deposits have been identified to date with economical RE concentrations. However, while most of them are in the feasibility study stage, others remain either being explored or untouched. In this context, the Bear Lodge in South Dakota, USA (a deposit associated with a carbonatite complex with an estimated 18 million tonnes of RE) is a potential RE deposit, which has attracted the attention of the U.S Government due to its high grade of REEs. However, this deposit is yet to be mined due to regulatory delays, despite the completion of environmental assessment and exploratory activities (Borzykowski, 2019). The Bear Lodge deposit was formed by magma derived from the subcontinental lithospheric mantle and it was modified by subduction-related metasomatism. Due to weathering, this deposit is oxidised to a depth between 120 and 180 m. The fresh carbonatite in the Bear Lodge deposit consists of RE minerals, such as burbankite, early-stage parisite-(Ce) and synchysite-(Ce) along with bastnaesite-(Ce) in minor quantities. In contrast, fluorcarbonates, cerianite and monazite-(Ce) are present in the oxidised zone. This deposit is enriched of LREEs, however REE distribution patterns differ based on the paragenesis (Chakhmouradian et al., 2017). Moreover, Araxà complex in Paranaiba Province, Southern Brazil is known for the vast production of Nb for the global market. This RE mineralization is associated with a carbonatite intrusion and it is mainly enriched of LREEs. The major RE mineral found in this deposit is monazite and there are minor RE minerals, such as burbankite, carbocernaite, ancylite and huanghoite (Traversa et al., 2001). Furthermore, the Kvanefjeld deposit in south Greenland is famous for multi-element resources, including REEs. According to the estimations in 2011, this deposit has about 6.6 million tonnes of REOs, in which about 0.25 million tonnes are heavy REOs (Zhou et al., 2016). The Zandkopsdrift deposit in South Africa also contains around 0.79 million tonnes of REOs, according to its reserve estimations in 2014. Preliminary feasibility studies in 2015 revealed that REE extraction is technically feasible and economically viable (Zhou et al., 2016). Even though mining of the Zandkopsdrift deposit was expected to commence in 2017 by the Frontier Rare Earth Limited, the current status is not yet reported.

3.3.1. Secondary RE deposits

Besides the primary RE deposits, secondary RE deposits, such as placers and offshore sediments are currently considered as valuable RE resources. RE placer deposits are formed by weathering and erosion processes of REE-bearing rocks, and they are mostly found in environments, such as streams, lakes, and shorelines. These RE placer deposits are widely distributed in the world, for example, in Australia, India, Brazil, Malaysia and Sri Lanka (Kanazawa and Kamitani, 2006; Amalan et al., 2018; Dushyantha et al., 2019). The erosion process of REE-bearing rocks also concentrates RE minerals, particularly monazite and xenotime (Table 5), along with heavy minerals, such as ilmenite and rutile. Therefore, monazite is recovered as a by-product during heavy mineral extraction processes from beach placer deposits, especially in the southern coast in India. In addition, xenotime is generally recovered as a by-product during tin placer mining (Van Gosen et al., 2014). RE resources can also be found in marine environments (i.e. as seafloor deposits). Deep-ocean manganese nodules and iron-manganese crusts found in the Pacific Ocean are identified as RE deposits with higher amount of HREEs than carbonatite related deposits (Hein et al., 2011; Wall, 2014). Deep-sea mud in the Pacific Ocean is also identified as low-grade RE resources with low thorium content (Kato et al., 2011). Industrial rare earth extraction from these has not been reported yet.

4. Global RE demand, production, consumption and China's role in REE industry

4.1. Global RE demand characteristics

With the impending rate of overall economic growth and the new developments in material applications, demand for REEs has been escalating dramatically during the past few decades. RE demand experienced its initial fast growth during the 1960s, due to the introduction of colour televisions to the market. At the beginning (in 1953), demand was around 1000 tonnes of REOs, which accounted for US$ 25 million. The demand then increased up to 66 thousand tonnes in 1997 and reached up to 125 thousand tonnes in 2008 (Zhou et al., 2016). However, Roskill (2015) reported that demand was 118 thousand tonnes of REOs in 2014 and the estimated demand will be around 170 thousand tonnes by 2020. Currently, over 60% of the demand for REOs is for new applications and it will continue to grow due to the frequent usage of REEs in clean technologies (Mancheri et al., 2019b). According to Kingsnorth (2016), demand for REEs could increase by 7–8% annually and Dutta et al. (2016) predicted an annual growth rate of 5% by 2020. Alonso et al. (2012) suggested that Nd and Dy demands will be increased by 700% and 2600%, respectively within the next two decades. Similarly, the price of the REOs is also increasing along with the demand. The cost of neodymium oxide, for example, is US$ 107 thousand per tonne in 2018 and it is expected to increase up to US$ 150 thousand by 2025 (Mertzman, 2019).

4.2. Global RE production and consumption

Fig. 2 graphically illustrates the history of RE production. In 2014, the calculated global value of RE products was worth around US$ 1.5 to 2 trillion (Tukker, 2014). However, around 130, 126, 132 and 170 thousand tonnes of REOs were produced globally in 2015, 2016, 2017 and 2018, respectively (United States Geological Survey (USGS), 2018). Fig. 3 illustrates the global RE production and consumption in 2016. In

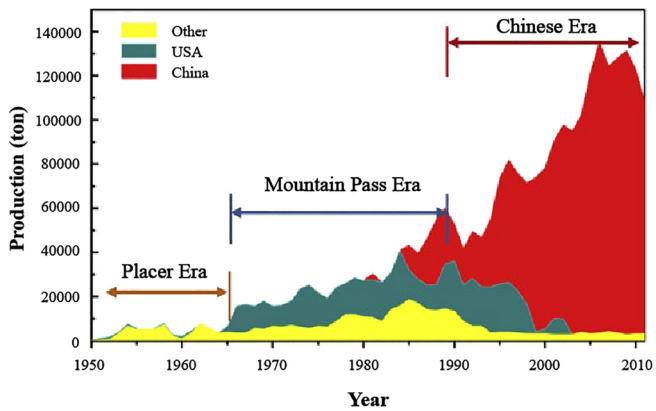

Fig. 2. Global REO production trends (Source: Long, 2011).

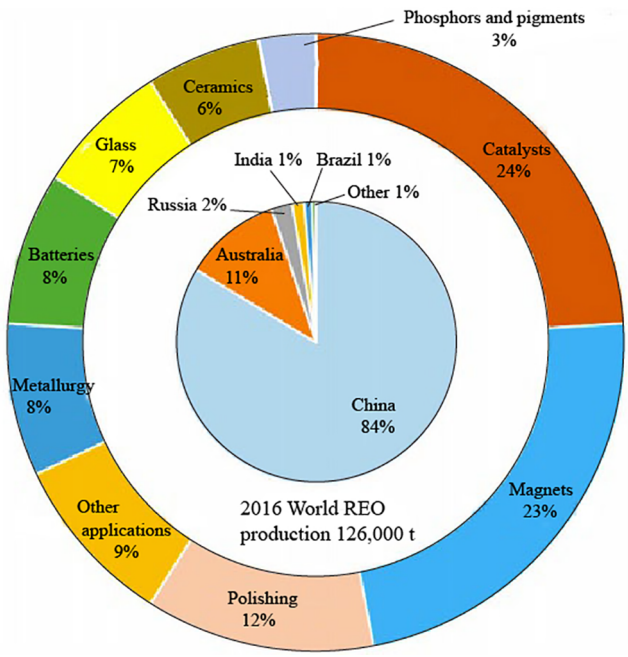

Fig. 3. The distribution of global RE production and consumption in 2016 (Sources: Long et al., 2012; Zhou, 2017).

this context, China has currently contributed to more than 90% of the global supply of REEs (Mancheri et al., 2019b). REOs production in China, for example, increased from 73 thousand tonnes to 120 thousand tonnes from 2000 to 2018 (United States Geological Survey (USGS), 2018). Since 2001, China has supplied RE products in the form of concentrates, REOs, chemicals, alloys, salts and metals (Tse, 2011; Liu et al., 2016; Ilankoon et al., 2018a). EU, USA and Japan collectively imported 78 thousand tonnes of REOs in 2008, in which 71 thousand tonnes were produced by China (Zhang and Shan, 2001).

In addition, China has experienced a marked increase in their RE consumption since 2000. By 2000, the Chinese RE consumption was about 19 thousand tonnes, whereas it reached a staggering 73 thousand tonnes by 2009 (global RE consumption in 2000 and 2009 were about 91 and 130 thousand tonnes, respectively) and this is equivalent to 380% increase compared to 2000 (Tse, 2011; Fernandez, 2017). Therefore, the Chinese dominated the RE market as the global consumer, besides being the global supplier (Section 5.5). Fig. 4 illustrates the production and consumption data of REOs in China from 2007 to 2015. Moreover, China is planning to accelerate automotive electrification to overcome the oil shortage and environmental concerns by 2030. This approach will heavily rely on REEs and their applications in

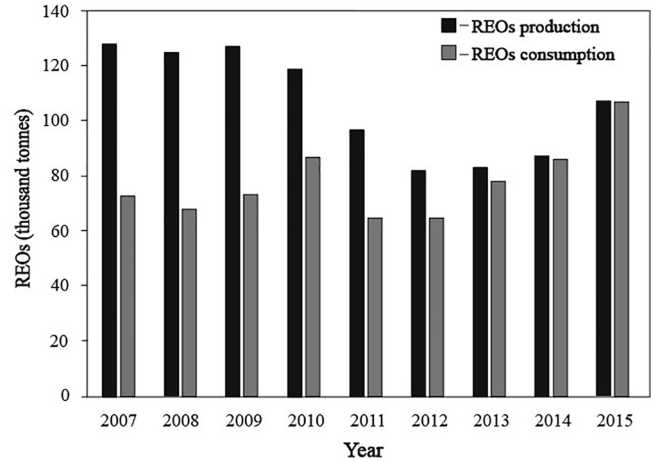

Fig. 4. China's RE production and consumption from 2007 to 2015 (Sources: China Industry Information Network, 2007–2015; The Chinese Society of Rare Earths, 2007–2015); Li and Yang, 2016; Ilankoon et al., 2018a).

electric vehicles. Therefore, the demand for REEs, such as Nd, Dy, La, Pr and Ce will rise precipitously during the next decade (Li et al., 2019).

4.3. China's dominance in RE market

China controlled their RE exports in 2010 to reduce environmental degradation and to build up a strategic stockpile of REEs, which can serve domestic demand in future (Humphries, 2010; Hurst, 2010). It triggered a global spike in RE prices and created anxiety among worldwide RE stakeholders, where they understood that steadiness of the RE supply chain was susceptible and there may be a shortage of raw materials for green energy technology developments in the future. Fig. 5 shows the indexed price of a few REOs from 2006 to 2016 and it shows a spike in indexed prices of REOs from 2010 to 2013. Therefore, the time period from 2010 to 2013 is known as "Rare Earth Crisis", where RE prices and demand were heavily affected by China's adopted RE export policies. This portrays the monopolistic grip that China has on REEs (Tse, 2011; Li and Yang, 2014; Voncken, 2016). To overcome these RE supply shortages, opening of new mines and abandoned mines have been considered outside China in order to increase the global RE

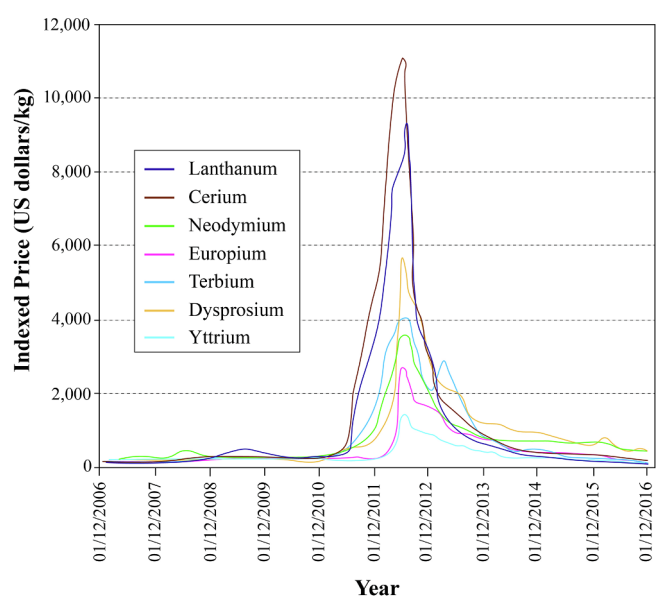

Fig. 5. Indexed prices for selected REOs from 2006 to 2016 (Source: Eggert et al., 2016).

production. However, by 2013, China increased their RE productions and removed export quotas. Therefore, the overall surplus was experienced in certain elements, such as Nd, Eu, Tb and Dy, whereas the RE price started to decrease (Fig. 5) (Mancheri et al., 2019a). However, China is still withstand as the dominant force in the RE industry even at lower prices for REEs (Chen et al., 2018).

4.4. China's illegal RE trading

Illegal RE trading in China has been increasing at a significant rate from 2007. It was mainly due to the imposed restrictions by the Chinese government on RE trading. On the other hand, tracing of the exact illegal RE mining and export quantities is a difficult task and therefore different agencies estimate different quantities (Ilankoon et al., 2018a). However, illegal REEs trade is estimated based on export and import quantity differences (Mancheri, 2016). China's illegal RE activities, mainly in two southern provinces: Jiangxi and Guangdong, has grown rapidly from 2007 to 2015, which accounted for about 25% of RE supply from China. During this period, 59 to 65% for HREE oxide and 14 to 16% of LRRE oxide productions were illegally produced in China (Nguyen and Imholte, 2016). This illegal RE production boom has caused RE prices to drop down due to the low-cost trading, and as a result, the legal operations were forced to offer low prices. Therefore, most of the RE mining companies in China incurred losses due to the plummet in RE prices in 2015 (Chang and Hui, 2015).

The Chinese government has now been restricting and controlling the illegal RE output and smuggling via regulating the market. In this regard, the government and Lynas Corp, the Australian RE producer, planned to install a system to trace the origin of the products (Jamasmie, 2016a; Paul and Stanway, 2016). The Chinese ministry of industry and information technology have taken initiatives in October 2016 to restrict illegal RE production, transaction and processing in China and address other internal issues, such as overproduction, less innovative measures, low efficiency and lax environmental standards in RE industry (Ilankoon et al., 2018a; Mancheri et al., 2019a).

4.5. China's current status in RE industry

Since the end of 2016, the RE prices have experienced a growth. For example, the prices of Pr-Nd oxides, which are primarily used in permanent magnets, have escalated by 72% from October 2016 to October 2017. The global demand for REEs is expected to rise continuously during the next decade (Chen et al., 2018) and this includes the required REEs for the implementation of emerging technologies. The RE industry thus heavily depends on the Chinese RE supply. It is envisaged that China's RE production will reach its peak levels in 2038–2045 with a peak production of 265–385 thousand tonnes (Wang et al., 2017). Therefore, the Chinese government has introduced new environmental and resource exhaustible taxes to control RE production and exports.

Currently, China produces primary RE products, such as permanent magnets, catalysts, luminescent and polishing materials, targeting the high-tech industries, especially the global renewable energy industry which has a promising future for RE applications (Research and Markets, 2019). By October 2019, China had filed 25,911 patents on all the REEs, whereas USA, Japan and the European Union had only filed 9810, 13,920 and 7280 patents, respectively. In addition, the number of Chinese filed patents related to REEs has escalated since 2011 compared to the rest of the world (Fig. 6, Eric, 2019b). Therefore, China is leading in emerging technologies associated with REEs, which indicate the expansions and shifts of the RE industry in China.

Due to the strategic importance of REEs in global high-tech industry, they have now become a diplomatic weapon. In this regard, China has the power to use REEs in trade wars against other countries. For example, China previously banned RE exports to Japan in 2010 due to a territorial dispute (Humphries, 2010). It created a significant impact on Japanese high-tech industry and REEs became the China's tool to win the trade wars. Similarly, a trade war has begun between the USA and China since 2018. In this context, the USA has imposed a 10% tariff on US$ 300 billion of products imported from China, including REEs effective from September 2019. The China Rare Earth Industry Association has decided that they will pass the tariffs on REEs to the US consumers. Therefore, China is ready to use REEs as a trade weapon even against the USA in their trade disputes (Eric, 2019b).

5. Secondary RE resources and RE recycling

Since primary RE resources are finite and their supply is at a risk of uncertainty, production and usage of REEs need to be ensured in a sustainable manner. This can be achieved by reducing the RE quantity in single-use products, recycling and reusing of RE products as secondary RE resources and finding sustainable alternatives or substitutes for REEs (Atwood, 2013). Reducing the RE quantity in end-use products has been made significant progress, especially in permanent magnets. Nissan, for example, was able to reduce Dy usage by 40% in a newly developed electric motor over conventional electric vehicle motor in 2012. In addition, LEDs contain a very low content of phosphors (about 1%) compared to CFLs. Since LEDs have a longer lifetime and higher efficiency than CFLs, LEDs have been more established in the lighting market. Therefore, RE demand for phosphors in high-efficiency lighting is decreasing continuously (Zhou et al., 2016).

When REEs containing materials are no longer economically valuable as industrial products, they are considered as waste materials and subsequently become secondary RE resources, namely, electrical and electronic waste (or e-waste), mine tailings, red mud and phosphogypsum. Recovering REEs from secondary resources has been a promising solution to alleviate impending challenges associated with RE mining and processing, such as removal of radioactive elements, energy requirements and resource accessibility (Schüler et al., 2011). Table 9 contains the currently available secondary streams for RE recycling and green recycling methods, such as bioleaching could reduce the environmental footprint of recycling. Recycling can be categorized as closed-loop and open-loop. In closed-loop recycling, recovered RE alloys will be used for similar applications, and however, this category has its challenges in collecting, sorting, components-separating and processing. In open-loop recycling, recovered REEs from RE alloys will be used in other applications (Koltun and Tharumarajah, 2014). Therefore, instead of primary mining operations, recycling of REEs from secondary resources will be an effective approach to fulfil the RE demand, independent of the Chinese rare earth export restrictions and price fluctuations.

5.1. E-waste

Electric and electronic equipment's components, such as printed circuit boards, cathode-ray tubes, batteries and magnets are categorized as e-waste (Ilankoon et al., 2018b). E-waste is a fast-growing waste stream throughout the world, growing at a rate of 3–5% per year, accounting for about 5% of municipal waste (Tan et al., 2015; Balde et al., 2017).

Due to the unique characteristics of REEs, they are indispensable in electric and electronic components in the modern world. Thus, REE-bearing components in e-waste have much higher RE concentrations than natural minerals (Tan et al., 2015). This justifies REE extraction from e-waste, though base and precious metal extraction has been the current norm in e-waste recycling. Neodymium-iron-boron (NbFeB) magnets, also known as RE magnets, used in many different electrical and electronic applications, such as in computer hard disk drives, loudspeakers and household electric appliances are recycled via hydrogen decrepitation. A significant amount of magnetic property (about 90%) is recovered by this technique (Jiles, 2015; Walton et al., 2015; Awais et al., 2017).

REEs such as Eu, Tb and Y are highly used in lamp phosphor

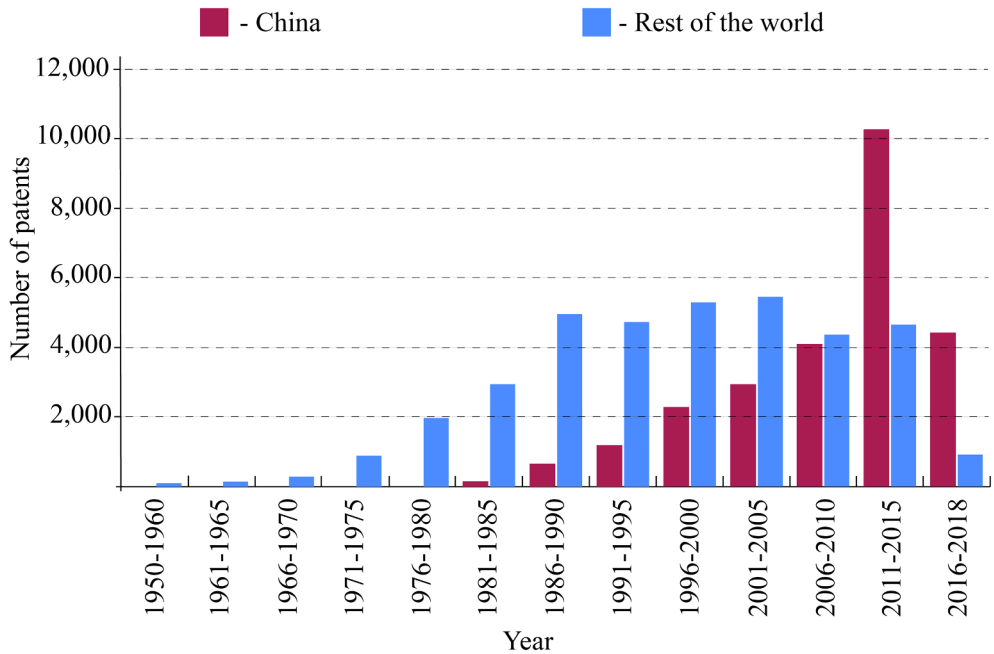

Fig. 6. Global patent filings in REEs held by firms in China compared to firms in rest of the world (Source: Eric, 2019b).

powders in lighting products due to the luminescent properties of REEs (Machacek et al., 2015). Since fluorescent lamp waste contains more than 20% of REEs by weight, the phosphor powder in fluorescent lamps is a rich source of Eu, Tb and Y (Gijsemans et al., 2018). It can be recycled for value recovery and recycled phosphor powder can be re-used in new lamps. Recycling of phosphor powder is used to recover individual phosphor components via physicochemical separations and REEs by chemical processes (Binnemans et al., 2013a). Since Eu and Y have high recoverability, those have been continuously extracted from red phosphor (Gijsemans et al., 2018).

RE alloys like misch-metal show hydrogen storage properties, and therefore, these alloys are highly used in rechargeable nickel metal hydride (Ni-MH) batteries. La, Ce, Pr and Nd (misch-metal) are predominantly used in these batteries and it is equivalent to 10% of REEs. In addition to recycling of Ni-MH batteries to recover Ni in stainless steel production, studies have focused on recycling Ni-MH batteries to recover REEs via hydrometallurgical or pyrometallurgical processes (Jowitt et al., 2018). Considering the potential of e-waste as secondary RE resources, sustainable RE recycling techniques still need to be developed and implemented.

5.2. Mine tailings

Mine tailings from RE deposits contain REEs in high concentrations due to the low recovery via currently available extraction processes. Mountain Pass mine tailing dams, for example, possess a REO content about 3–5% and can be considered as viable RE resources. REEs are also enriched in uranium, iron ore and titanium mine tailings in Australia, Kazachstan and Sweden (Jha et al., 2008; Peelman et al., 2016a). Kiruna iron ore mine tailings in Sweden, for example, is recognised as a potential RE resource and the tailings contain about 5000 ppm of REEs after the beneficiation. About 8 million tonnes of mine tailings are being annually produced, and thus, it is capable of producing 15 thousand tonnes of REEs. In addition, 50–100 million tonnes of tailings are remained in the tailing ponds which could also be used to recover REEs (Peelman et al., 2018). Peelman et al. (2016b) reported that acid leaching of iron ore mine tailings in the Kiruna mine extracted HREEs, such as Eu, Dy and Y with leaching efficiencies more than 75%. This implies the economic viability of mine tailings for RE extraction as a secondary RE resource.

5.3. Red mud

Bauxite is the primary aluminium ore (or main source of aluminium), which contains about 30–50% of alumina along with trace elements, such as calcium, sodium, zinc, gallium and REEs (Ochsenkühn-Petropulu et al., 1995; Smirnov and Molchanova, 1997). The Bayer process is applied to extract aluminium from bauxite, whereas it generates a solid residue, which is known as bauxite residue or red mud. Despite minor applications in cements and ceramics, red mud does not have industrial-scaled applications in any sector. Therefore, long-term red mud storage has become a storage (i.e. limited space for future mining activities) and environmental issue (Borra et al., 2015). REEs, especially Sc, are enriched in red mud during the Bayer process and they can be extracted from red mud either by direct leaching or by smelting followed by leaching (Borra et al., 2015).

5.4. Phosphogypsum

Production of phosphoric acid via acid digestion of phosphate rocks generates phosphogypsum as the main by-product of the process. Phosphogypsum mainly contains calcium sulphate dihydrate, $CaSO_4{\cdot}2H_2O$, along with some other trace elements, such as uranium, thorium and REEs (Koopman and Witkamp, 2000; El-Didamony et al., 2011). Generally, phosphate rocks contain about 0.01–0.1% of REEs in which cerium, lanthanum and neodymium contribute to 80% of the total RE content. During the phosphoric acid production process, about 70–85% of REEs in phosphate rocks are enriched in phosphogypsum. Although RE content in phosphogypsum is low compared to the RE deposits, the generated phosphogypsum volume is very high and thus phosphogypsum can still be considered as a secondary source of REEs (Habashi, 1985; Skorovarov et al., 1992; Zielinski et al., 1993; Binnemans et al., 2013b). Phosphogypsum waste in the Wizów Chemical Plant in Poland, for example, has been accumulated since 1948, containing lanthanides (as Ln_2O_2) about 0.3–0.7% by weight. This waste could be used to produce 6–10 thousand tonnes of REEs (Grabas et al., 2014; Kulczycka et al., 2016). Moreover, Rychkov et al. (2018) introduced a process to recover 97–99% RE concentrate from phosphogypsum containing 0.43–0.52% of REEs in the Sredneuralsky Copper Smelting Plant in Russia.

In addition, coal and its by-products, such as coal middling and

Table 9
Availability of REE-containing streams for recycling (Source: Binnemans et al., 2013a).

Material stream and application	REEs	Present/future contribution
1. Pre-consumer production scrap and residues Magnet swarf and rejected magnets	Nd, Dy, Tb, Pr	Increasing
REE containing residues arising during metal production/recycling	all	
Post-smelter and Electric Arc Furnace residues	Ce, La, critical REEs	Future levels depend on End-of-Life pre-smelter recycling
Industrial residues (phosphogypsum, red mud, etc.)	All	Relatively stable
2. End-of-Life products containing…		
Phosphors	Eu, Tb, Y (Ce, Gd, La)	
Fluorescent lamps (straight/curved)	Eu, Tb, Y (Ce, Gd, La)	Relatively stable
Compact fluorescent lamps (CFLs)	Eu, Tb, Y (Ce, Gd, La)	Increasing
LEDs	Y, Ce	Increasing
LCD Backlights	Eu, Tb, Y (Ce, Gd, La)	Relatively stable
Plasma Screens	Eu, Tb, Y (Ce, Gd, La)	Relatively stable
Cathode-ray tubes (CRTs)	Eu, Y	Sharply decreasing
Others (speciality applications)	Also Tm	
Permanent NdFeB magnets	**Nd, Dy, Tb, Pr**	
Automobiles (small magnets as motors, switches, sensors, actuators, etc.)	Nd, Dy, Tb, Pr	Relatively stable
Mobile phones (loudspeakers, switches, microphones, etc.)	Nd, Dy, Tb, Pr	Relatively stable
Hard disk drives (HDDs)	Nd, Dy, Tb, Pr	Will decrease (due to solid state devices)
Computers and peripherals (cooling fans, switches, drive motors, scanner head motors, small HDDs etc.)	Nd, Dy, Tb, Pr	Relatively stable
Consumer electric and electronic devices (kitchen utensils, handheld tools, electric shavers etc.)	Nd, Dy, Tb, Pr	Relatively stable
Industrial applications (electric motors etc.)	Medium Dy level	increasing (due to increasing energy efficiency demands for electric motors)
Electric bicycles (motor)	Higher Dy level	Increasing (especially in China)
Electric vehicle and hybrid electric vehicle motors	Higher Dy level	Increasing (but inertia for availability)
Wind turbine generators		Increasing (but inertia for availability)
Other magnet applications	Sm (in SmCo magnets)	Relatively stable
Nickel metal hydride batteries	La, Ce, Nd, Pr	
Rechargeable batteries		Increasing
Electric vehicle and hybrid		Increasing
electric vehicle batteries		
Others	Depending on application	Depending on application
3. Landfilled REE containing residues		
Industrial residues (phosphogypsum, red mud, etc.)	All	Depending on residue type

refuse are also identified as potential alternative RE resources (Huang et al., 2018). The Junger coal field in China, for example, has the potential of supplying 12 thousand tonnes of REOs (Seredin and Dai, 2012). Moreover, oil sands in Alberta, Canada is used to extract bitumen, where sand itself contains low RE concentrations and tailings accumulated in solvent recovery unit contained average concentration of 1100 ppm of REEs. Therefore, the tailings from bitumen extraction from oil sand elucidate the potential of a secondary source of REEs, though it has not yet exploited (Roth et al., 2017).

6. Current status of secondary RE resources and RE substitution

RE extractions from secondary sources are still under development and thus RE recycling accounted only for less than 5% of the global RE

supply in 2019 (Linnenkope, 2019). Although, various technologies have been introduced for RE extraction, those are still in its infancy due to the impending challenges, such as extraction efficiency and selectivity, and process economic considerations (Peelman et al., 2016a). Therefore, novel extraction techniques combined with conventional methods are crucial to facilitate RE extraction from secondary sources. In this context, efficient RE recycling helps to conserve finite and non-renewable RE resources in the globe.

The substitution of REEs is also currently drawn attention to address the RE scarcity. REE can be substituted by another REE, which is more abundant and cheaper for a given application (Carbonaro et al., 2016). In permanent magnets, for example, less abundant Sm is substituted by more abundant Nd. As a result, SmCo magnets are replaced by NdFeB magnets since 1985. Furthermore, REEs can be replaced by non-REEs. For example, RE-free electric motor was built by Japanese researchers and Hybrid Electric Vehicle Technologies in 2011. In addition, RE phosphors in LEDs are substituted by silicon quantum dot phosphors, whereas organic lighting devices are becoming good candidates to replace REE-based lighting. However, non-RE substitution has still been challenging due to its less efficiency (Zhou et al., 2016; Ganguli and Cook, 2018) and more future studies are intended.

7. Environmental problems and health issues related to RE mining and processing

Despite the global expansion of the RE industries during the last decade, detailed toxicological investigations on REE-induced health problems have been relatively scarce. Exposure of the people to RE toxicity can occur in various environments, such as iatrogenic, occupational and environmental routes. Since Gd is used as a contrast agent in magnetic resonance imaging (MRI), anomalously high Gd concentrations in the femoral head bones of patients have been identified due to Gd exposure via iatrogenesis. This excess Gd accumulation causes medical conditions, such as acute kidney failure, nephrogenic systemic fibrosis and even death (Chien et al., 2011; Bernstein et al., 2012). However, toxic side-effects of Gd ions is markedly reduced using the technique of chelated complex formation in MRI contrast agents (Xiao et al., 2016).

Occupational and environmental exposures of REEs are evident in several stages of the RE industry, such as mining, processing, transportation, waste disposal and decomposition (Rim, 2016). Table 10 summarises the general environmental concerns related to mining and processing of REEs. Pollution due to the chemical reagents, such as sulphates, oxalates and extract solvents used in extraction, processing and recycling of REEs is another aspect of environmental issue, if those are discharged to the environment without any pre-treatments (De Baar et al., 1983; Ali, 2014). These environmental impacts have already created a social resistance to RE mining in countries like China and India.

People who are working in RE mining and processing industry expose to long-term rare earth dust exposure. Lung diseases and pneumoconiosis are thus reported among workers in the rare earth industry due to the inhalation of dust containing lanthanides, especially cerium oxide (Sabbioni et al., 1982; McDonald et al., 1995). Bioaccumulation of REEs and pathological changes are reported among local residents, who live near RE mining areas (Pang et al., 2002; Tong et al., 2004). In addition, it is reported that prolonged exposure to Ce is associated with lung pathologies and heart diseases in India during monazite mining and processing (Chakhmouradian and Wall, 2012). Furthermore, cerium oxide (CeO_2) nanoparticles are used as a catalytic additive in diesel fuel and it results in the emission of CeO_2 nanoparticles as a diesel exhaust particulate matter, causing air and soil pollution. It also poses occupational and environmental exposure of REEs to the humans to cause Ce-induced diseases (Pagano et al., 2015; Rim, 2016).

However, the radioactivity of the associated elements, such as thorium (Th) and uranium (U) in rare earth minerals is the critical environmental concern of RE deposits (Massari and Ruberti, 2013; Mehmood, 2018). A high level of radiation has been reported in monazite mining and storage areas in India, and it has been eventually linked to different human health hazards (Padmanabhan, 2002). In addition, strong public protests citing the adverse impacts of the radioactive wastes were seen in Malaysia in November 2008 against the issuance of the operating licensee for the Lynas Company to process REEs in Malaysia (Phua, 2016). Australia experienced a significant decline in monazite exports from 1989 to 1992 due to the radioactivity concerns and thus RE companies preferred RE concentrates from China instead of Australia (Koltun and Tharumarajah, 2014). These radioactive components make RE extraction expensive and challenging. In

Table 10
Environmental issues associated with REE mining and processing (Source: Schüler et al., 2011).

Risk	Affected compartments	Relevant toxic compounds
Overtopping of tailing dam	Groundwater, surface water, soil	**Water emission**
Collapse of tailing dam by poor construction	Groundwater, surface water, soil	• Radionuclide
		• Heavy metals
Collapse of tailing dam by seismic event	Groundwater, surface water, soil	• Acids
		• Fluorides
Pipe leakage	Groundwater, surface water, soil	**Air emission**
Ground of tailing pond not leak-proof	Groundwater	• Radionuclide
		• Heavy metals
Waste rock stockpiles exposed to rainwater	Groundwater, surface water, soil	• HF, HCl, SO2, etc
Dusts from waste rock and tailing	Air, soil	
No site-rehabilitation after cease of mining operations	Land-use, long-term contaminated land	
Processing without flue gas filters	Air, soil	
Processing without wastewater treatment	Surface water	

order to mitigate the radioactivity issue, international guidelines and regulations introduced by the International Atomic Energy Agency (IAEA) and the US Environmental Protection Agency (EPA) are currently used in REE mining and processing worldwide (Ault et al., 2015).

Furthermore, RE mining and processing techniques consume a lot of energy gained from fossil fuels which cause environmental implications such as carbon emission. For example, production of 1 kg of Sm-Eu-Gd oxide emits about 55 kg of CO_2 (Weng et al., 2013) which is significantly high compared to 2.6 kg of CO_2 emitted during the production of 1 kg of Cu (Northey et al., 2013). Thus, carbon emission in RE mining and processing is another environmental problem which can cause adverse environmental consequences, such as global warming and climate change (Haque et al., 2014; Mehmood, 2018).

Therefore, stringent environmental enforcements need to be taken by the relevant authorities to minimize these environmental problems associated with RE mining and processing. Rare earth industry should focus to achieve the United Nations sustainable development goals (SDGs), such as good health and well-being (Goal 3), clean water and sanitation (Goal 6), responsible production and consumption (Goal 12) and climate action (Goal 13) to ensure a better future for this planet (The United Nations: Sustainable development goals, 2018).

8. Conclusions

REEs play a key role in high-technology, non-toxic and environmentally friendly inventions in industrial revolution towards a green economy. Due to their superior chemical and physical properties, REEs are widely used in a broad and rapidly expanding range of applications in sectors, such as metallurgy, energy, military and agriculture. Thus, RE demand is rising and expected to result in RE scarcity and uncertainties in market price in the near future. Moreover, the current supply of REEs seems to be lagging with respect to the demand and supply is likely to be disrupted, especially due to current trade wars between RE producers and consumers. Therefore, exploration of new RE mineral deposits and re-opening of closed RE mines were discussed in order to address the ever-increasing demand. In this regard, understanding RE occurrences, genesis of major RE deposits and their mineralogy is significant for the determination of feasibility of mining operations, processing and refining. The Bayan Obo, Mountain Pass, Mount Weld and ion-adsorption clays in China are the most prominent RE deposits in the world. Since their genesis is mostly related with carbonatite associated with alkaline complexes, such geological associations must be explored for new potential RE resources. In addition, recycling of REEs from secondary sources is also a promising alternative for REE-related issues, such as high demand, scarcity, price fluctuation and security of supply. However, certain technologies in the RE recycling industry are still in its infancy. Thus, countries without RE endowments should mainly focus on developing novel RE recycling techniques, combined with conventional techniques, to achieve innovative and industrially viable RE recycling processes.

Moreover, governments and relevant authorities should introduce the United Nations SDGs to minimise health, environmental and social impacts created by the radioactive and non-radioactive contaminants in the RE industry. It will reduce the social resistance towards the RE industry and will be crucial to maintain the social sustainability associated with RE exploration, mining, processing and recycling.

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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