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Original Paper

The Rare Earth Elements: Demand, Global Resources, and Challenges for Resourcing Future Generations

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The rare earth elements (REE) have attracted much attention in recent years, being viewed as critical metals because of China's domination of their supply chain. This is despite the fact that REE enrichments are known to exist in a wide range of settings, and have been the subject of much recent exploration. Although the REE are often referred to as a single group, in practice each individual element has a specific set of end-uses, and so demand varies between them. Future demand growth to 2026 is likely to be mainly linked to the use of NdFeB magnets, particularly in hybrid and electric vehicles and wind turbines, and in erbium-doped glass fiber for communications. Supply of lanthanum and cerium is forecast to exceed demand. There are several different types of natural (primary) REE resources, including those formed by high-temperature geological processes (carbonatites, alkaline rocks, vein and skarn deposits) and those formed by low-temperature processes (placers, laterites, bauxites and ion-adsorption clays). In this paper, we consider the balance of the individual REE in each deposit type and how that matches demand, and look at some of the issues associated with developing these deposits. This assessment and overview indicate that while each type of REE deposit has different advantages and disadvantages, light rare earth-enriched ion adsorption types appear to have the best match to future REE needs. Production of REE as by-products from, for example, bauxite or phosphate, is potentially the most rapid way to produce additional REE. There are still significant technical and economic challenges to be overcome to create substantial REE supply chains outside China.

KEY WORDS: Rare earth elements, Resources, Supply chain, Minerals processing.

INTRODUCTION

The rare earth elements (REE) include the lanthanides, from lanthanum (La) to lutetium (Lu), and are often also considered to include the chemically similar elements yttrium (Y) and scandium (Sc). They are typically divided into two groups, the light and heavy rare earth elements (LREE and HREE, respectively), with the LREE including La, cerium (Ce), praseodymium (Pr), neodymium (Nd) and samarium (Sm). The HREE then extend from europium (Eu) to Lu. Yttrium is often grouped with the HREE due to its similar properties. Scandium is not considered with the REE in this paper. The REE are widely viewed as critical metals, because they are extensively used in modern technology, but all aspects of their supply chain are dominated by China (Massari and Ruberti 2013; EC 2014; Wall 2014). Most recently, some researchers have studied

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the criticality of individual REE (Du and Graedel 2013; Nassar et al. 2015) and there is increasing awareness that treating them as a single group oversimplifies some of the major issues.

In the Earth's crust, there is a general trend of decreasing abundance of REE with increasing atomic number. Superimposed upon this is the 'Oddo–Harkins effect'; elements with an even atomic number are more abundant than those with odd atomic numbers. This means that Ce is the most abundant of the REE in the Earth's crust; in contrast, Lu is genuinely rare. Most natural REE ores are dominated by La, Ce and Nd with much smaller amounts of the HREE. There are many challenges in processing these ores to create the individual metals required by the market, because of the wide range of possible ore minerals that each require a different beneficiation process (Jordens et al. 2013); and because of the additional steps required to separate out each of the REE (Xie et al. 2014; Machacek and Fold 2014). Almost inevitably, the natural abundance of the different elements in ore does not match market demand, creating the 'balance problem' (Binnemans and Jones 2015). There are several ways to manage the balance problem, including diversification of the resources that are exploited, recycling, substitution of other elements for the REE, and development of new uses for the most abundant REE (Binnemans and Jones 2015). In this paper, we consider how the first of those options might be addressed. We review current and predicted 10-year market demand for REE, identifying the most economically important members of the group. We compare this to known types of natural resources, in order to identify the types of deposits that are likely to be most suitable for future development, and consider the challenges associated with developing these deposits. Recycling of rare earths (the 'urban mine') is not considered in this paper, but has been reviewed elsewhere (Binnemans et al. 2013).

CHANGING DEMAND FOR THE RARE EARTH ELEMENTS

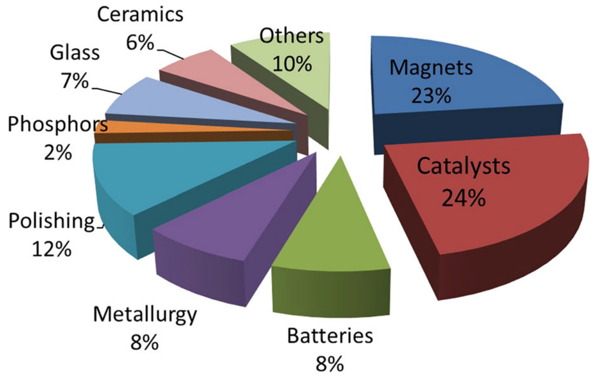

Figure 1. Current uses of REE, showing share of REE market. Data from Roskill (2016b).

Since their initial discovery and extraction, the uses of REE have changed from rare earth mischmetal used in lighter flints to high-purity separated rare earth metals being used in advanced electronics, lighting, power generation and military applications (Fig. 1). As a result, demand for REE has experienced strong growth from 75,500 tonnes (t) of rare earth oxides (REO) in 2000 to 123,100 t REO in 2016 (Roskill 2016b). As the various end-uses have changed, the types of REE products consumed have also altered. Historically this has been seen in the use of elements such as Eu and terbium (Tb) and more recently Lu in lighting, the use of La in specialist glass products, and the development of REE permanent magnet alloys increasing consumption for Sm, Nd and dysprosium (Dy).

In the developed world, REE are integral to many industrial, commercial and residential appliances and in the increasing electrification of vehicles. Though REE may only be used in very small volumes, they can provide performance or longevity benefits that some products rely upon, often making them difficult to substitute (Smith Stegen 2015). In the years to 2026, traditional applications will continue to lead demand growth for REE, though the development of new products and technologies could alter the demand for REE, both in terms of volume and the specific consumption of the individual elements used.

Over the next 10 years, the most disruptive technology for the consumption of REE is forecast to be the growth in hybrid electric vehicles (HEVs) and full electric vehicles (EVs), which are expected to cause wholesale changes in the volumes and types of raw materials consumed by the automotive industry. Production of HEVs and EVs is forecast to increase from 2.3 million units in 2016 to over 10.1 million units in 2026 (Roskill 2016a), as nearly all major automotive manufactures have developed HEV and EV models. EV models offer much cheaper running costs over the life of the vehicle than HEV models and are forecast to show the

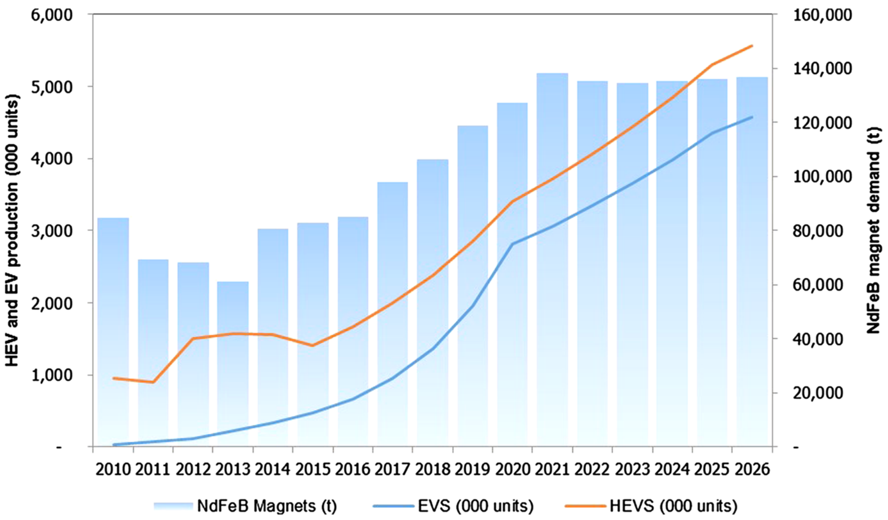

Figure 2. Forecast production of HEVs and EVs versus NdFeB magnet demand, 2010–2026. Data from Roskill (2016b).

highest production growth rates in the years to 2026. This production growth is likely to drive greatly increased demand for neodymium-iron-boron (NdFeB) magnets (Fig. 2).

NdFeB magnets are not unfamiliar to the automotive industry, with most internal combustion engine (ICE) vehicles, HEVs and EVs containing between 40 and 100 small electric motors in components such as windscreen wiper motors and air conditioning systems. However, the ongoing electrification of automotives has increased the intensity of use in all vehicle types. NdFeB magnets are used in the powertrain in HEVs and EVs as well as in numerous other smaller applications, with up to 2.5 kg of NdFeB magnets being used in the powertrain of current models. In 2016, a total of 5000 t of NdFeB magnets were estimated to be used in the drive trains of HEVs and EVs. The magnets in these powertrains are required to operate under high temperatures (+150 °C) while retaining high coercivity, requiring the addition of metals including Dy to the magnet alloys. Though many magnet manufacturers are developing NdFeB magnet alloys with lower Dy contents, automotive powertrain applications will continue to require higher-Dy content alloys to reliably operate at these higher temperatures (Hao 2016). As a result, the forecast increase in HEV and EV output will require large volumes of Nd, Pr and Dy.

There are competing technologies to NdFeB permanent magnet motors for automotive applications, which have been developed since 2011–2012 when REE prices increased sharply and supply availability became problematic for manufacturers (Riba et al. 2016). However, technologies such as induction motor drive trains are less energy efficient than NdFeB permanent magnet motors, though their lack of exposure to REE prices and supply fluctuations has made them necessary cost-effective alternatives.

Electric vehicles are expected to show the strongest growth in demand, though other applications for NdFeB magnets in renewable energy generation will become increasingly important, as governments and industries make efforts to meet stringent climate change and emissions standards. In 2016, wind turbines were the second-largest end-use applications for NdFeB magnets behind consumer electronics, consuming around 8000 t NdFeB magnets. Global wind capacity is growing rapidly, with the Global Wind Energy Council forecasting cumulative capacity to grow by 12–14%py through to 2020, reaching 790 GW (GWEC 2015). Installed capacity is likely to reach 870 GW in 2021 and could grow to greater than 1330 GW by 2026 despite slowing growth rates (Fig. 3). China is the largest wind power generator, increasing installed capacity by over 70 GW between 2013 and 2015, though the planned removal of subsidies in 2016 has accelerated the installation of new capacity during this period.

Though figures vary by manufacturer and product, the direct-drive permanent magnet generator (DDPMG) design for wind turbines typically requires the largest volumes of NdFeB magnets at

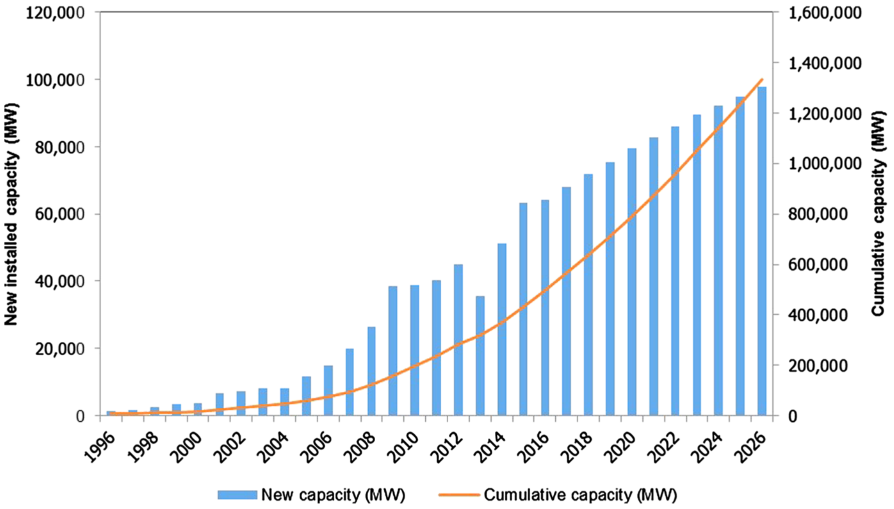

Figure 3. Global new and cumulative wind turbine capacity installation, 1996–2026. Data from Roskill (2016b).

500–700 kg/MW of installed capacity. Hybrid designs use much smaller amounts of NdFeB magnets, typically between 100 and 200 kg/MW of installed capacity. Newer DDPMG technologies have become commercially available for large-size turbines, used mainly in offshore wind farms, which is expected to increase the volume of NdFeB magnets consumed per unit. NdFeB magnets for wind turbines typically contain low or zero Dy in the magnet alloys as the temperature range of operation is controlled by air ventilation. As a result Nd and Pr will be critical to supporting growth in wind turbines using direct-drive permanent magnet technologies, though they face a strong substitution threat from ferrite magnets and gearless turbine technologies if REE prices and availability become unfavorable to manufacturers.

NdFeB magnet consumption in the years to 2026 will be driven by hybrid and electric vehicles and wind turbines, though the use of these magnets in other applications will support further demand growth. The use of rare earth permanent magnets in motors and sensors of robotic production equipment and machinery is forecast to increase as production lines in major manufacturing nations become more automated. The International Federation of Robotics estimates global production of industrial robots to increase from 290,000 units in 2016 to 414,000 units in 2019 (IFoR 2016), largely for use in the automotive, electronics/electrical and metals, chemicals and plastics industries. China is expected to show the highest uptake of industrial robotics, with demand increasing by 21% per year between 2016 and 2019 reaching 160,000 units.

Rare earths are often used as additives in glass fibers for fiber optic applications to improve data transfer speeds. Erbium (Er) is the most commonly used dopant with ytterbium (Yb) used in larger-scale optical fibers. Other rare earths including thulium (Tm) and Pr have also been used in some optic fibers though these are not commercially produced. Optical fiber cabling for short-distance communication has grown globally since 2010, as copper cabling has been replaced in telephone, television and local area network infrastructure to increase data transfer rates. In long-distance communication, rare earth-doped optical fibers are used in amplifiers, which have been replacing more expensive and less efficient electronic repeaters. Er-doped glass fiber production increased 8–10% per year between 2000 and 2016, largely in China. Similar growth rates for erbium glass fiber production are expected in the years to 2026 as higher-speed and larger volume data transfers will be required by both commercial and domestic consumers.

Production of the two lightest rare earths, La and Ce, is forecast to substantially exceed demand over the next 10-year period, as mines focus on the production of rare earths used in magnet alloys. Prices of La and Ce are therefore likely to remain low. Despite this oversupply, these elements are both critical to future generations, either in existing widespread technologies or technologies under development. The use of La and Ce in fluid catalytic cracking catalysts for the petroleum industry and for auto-catalysts will continue to be the largest end-use market for the two elements in terms of volume, though a range of other products use La and Ce as essential raw materials. There has also been an effort to identify new applications for La and Ce, particularly in China, as a result of the large forecast supply surplus. The Baotou Research Institute of Rare Earths (BRIRE) has developed La- and Ce-stabilized PVC products (Li et al. 2013, 2016), shown to have stability advantages over PVC products using other commonly used stabilizers such as calcium, barite, tin and lead. The volume of global PVC production was around 45 Mt in 2016, and the incorporation of even small percentages of lanthanum and cerium into PVC products could represent a sizeable end-use market for rare earths.

Lanthanum is used as an additive to improve the refractive index, decrease dispersion and enhance chemical stability in La-series optical lenses, mainly used in wide-angle lenses for consumer electronics. Yttrium and gadolinium (Gd) may be used as a replacement for lanthanum, though their cost premium makes them unattractive substitutes. The increase in production of smartphones and tablets containing optical lenses has seen a surge in demand for La-series glass with production in 2016 reported to total >6000 t, forecast to increase to >10,000 t in 2020. The development of cerium-iron-boron (CeFeB) magnets in China has been seen as a low-cost alternative to NdFeB magnet materials with less supply availability risk. Though CeFeB magnet alloys are significantly cheaper to produce, they do not have the high-coercivity or temperature range of operation that NdFeB and Dy-NdFeB magnet alloys possess, which many end-use applications require. As a result, CeFeB magnets are likely to be used only in low end products and their production and use outside of China will be limited.

The use of rare earths in phosphors has been in decline since the development and commercial production of LED technologies over fluorescent lamps, which has changed the volume and types of rare earths used in phosphor materials. Fluorescent lamps use Y as a host material and consume Eu, La and Ce as dopant materials, while LED technologies typically use Y and Lu as the host materials, particularly in glow lighting, albeit in much smaller volumes. Europium and Tb are still used as small-volume dopants in LED lighting products. LEDs are expected to continue replacing fluorescent lamps in the years to 2020, reducing demand for Y, Eu and Tb in phosphors, though warm-glow lighting has become more popular in commercial and residential lighting and demand for Lu is forecast to increase.

REE will remain critical for future generations, allowing for further improvements in product miniaturization, performance and efficiency. There are substitutes and alternative technologies to many REE-bearing products, and if prices and supply availability become unacceptable for manufacturers, this could result in rare earths being designed out of future technology development. Growth is forecast in a number of REE-containing applications requiring multiple rare earth products. However, demand for Nd and Pr in magnet alloys and to a lesser extent Dy in high-temperature magnet alloys is expected to ensure that these are the most critical rare earths both in terms of demand and supply. The increase in HEV and EV production will drive demand for Dy-containing NdFeB permanent magnets, while wind turbines and robotics will drive demand for low-Dy or Dy-free NdFeB magnets. Demand for Nd oxide and Pr oxide is forecast to increase by 4.7% per year between 2016 and 2026, while demand for Dy oxide is forecast to increase by 5% per year, though from a much lower starting base (Roskill 2016b). The use of rare earths in other applications such as optical glass, lighting and advanced ceramics will remain vital to their performance and future growth, increasing demand for REE in total by 4.4% between 2016 and 2026 reaching over 190,000 t REO. Figure 4 shows how this demand is forecast to be divided between the individual REE. In order to address the balance problem, the ideal natural REE resources would be those that match this demand for the individual elements.

REE RESOURCES

The majority of the world's REE are still derived from natural (primary) resources, although there is a substantial research and development effort on recycling of REE from manmade (secondary) resources (Binnemans et al. 2013). Natural REE deposits can be divided into a number of different categories on the basis of their geological associations, and various publications have used similar sets of categories (Chakhmouradian and Wall 2012; Wall 2014; Goodenough et al. 2016; Verplanck and Hitzman 2016). They include deposits formed by high-temperature (magmatic and

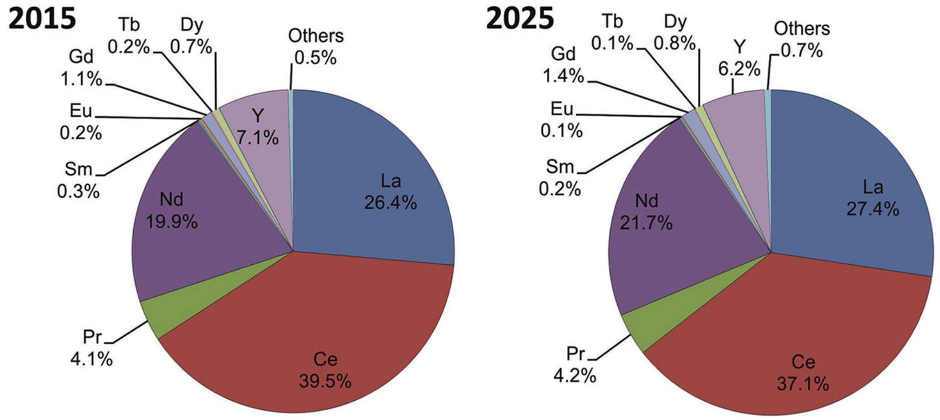

Figure 4. REE market demand by element in 2015 and forecast for 2025. Data from Roskill (2016b).

hydrothermal) processes, typically associated with carbonatites, alkaline igneous rocks, and hydrothermal systems; and deposits formed by low-temperature processes (erosion and weathering) such as placers, bauxites, laterites and ion-adsorption clays. An important aspect of understanding these different deposit types, and considering their potential, is the REE mineralogy (Goodenough and Wall 2016). There are over 100 potential REE ore minerals, but only very few of these have been successfully processed and the REE extracted (Jordens et al. 2013). In the section below, we consider each deposit type, the likely mineralogy and the potential for that deposit type to meet the forecast demand for different REE. For many deposits, bulk analyses of ore divided into the individuals REE are not publicly available, so we draw on representative samples from the published literature.

Carbonatites

Carbonatites, igneous rocks containing >50% carbonate minerals, represent the main source of global REE at the time of writing. The producing mines at Bayan Obo and Maoniuping in China, and Mt Weld in Australia, as well as the recently closed Mountain Pass mine in the USA, are all in fresh or weathered carbonatites; and many other carbonatites have been explored (Kynicky et al. 2012; Smith et al. 2016; Verplanck et al. 2016). Most carbonatites show significant REE enrichment when compared to crustal abundances, although economic enrichments are most commonly found only in the latest and most highly evolved parts of a carbonatite intrusion (Wall and Mariano 1996).

Carbonatites may be large and high-grade—particularly so at Bayan Obo (Smith et al. 2015)—but are characterized by intense LREE enrichment (Figs. 5 and 6). They commonly contain a wide range of REE-bearing minerals (Verplanck et al. 2016). These include a number of REE-carbonates such as bastnäsite, parisite and synchysite, all of which are typically LREE enriched. Of these, bastnäsite has a proven processing path (Jordens et al. 2013; Krishnamurthy and Gupta 2015) and is the main ore mineral at Bayan Obo and Mountain Pass (Castor 2008; Smith et al. 2015). Many carbonatites also contain REE-bearing phosphate minerals, notably apatite and monazite.

The current situation is that mining and processing of a carbonatite ore to produce one kg of Nd will generate large amounts of La and Ce, leading to oversupply, but will only produce small amounts of valuable Dy (Fig. 6). The current focus on carbonatite ores essentially drives the balance problem for rare earths. In fact, previous work has shown that on the basis of individual REE ratios alone, Bayan Obo is one of the least promising of all REE ores (Seredin 2010). The continued importance of this deposit is due to its large size, the established processing capabilities, and the fact that the REE were first mined there as by-products of iron ore (Verplanck et al. 2016).

Alkaline Igneous Rocks

The second main group of ‘hard-rock’ REE deposits is normally described as being associated with alkaline silicate igneous rocks, but this encompasses a great deal of variability. Within this

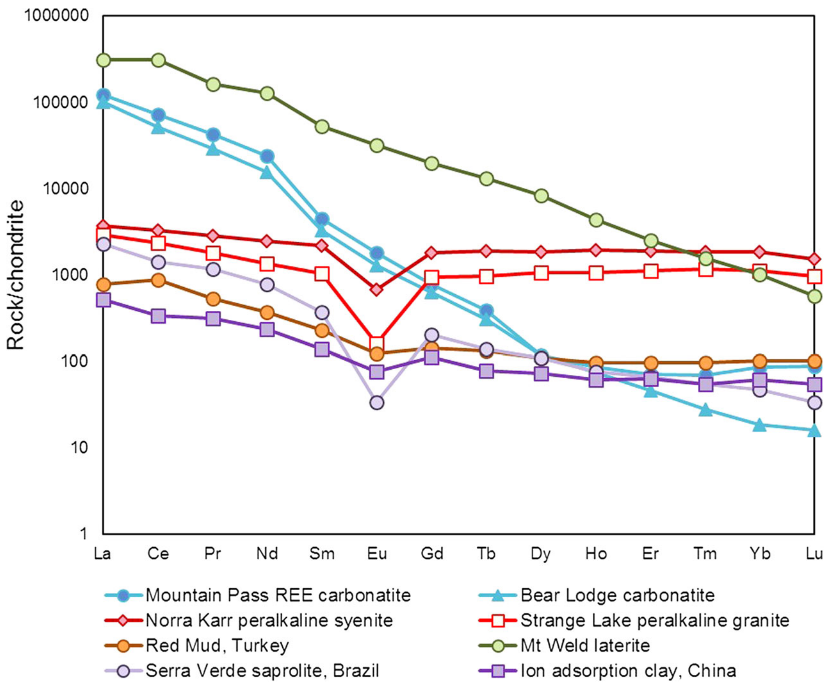

Figure 5. Chondrite-normalized plot showing representative samples from a number of REE deposits. Data for Mountain Pass (sample 11PV01), Bear Lodge (sample GRC-32) and Mt Weld (sample GRC-30) from Verplanck et al. (2016); for Norra Kãrr (sample PGT 407497) from Sjöqvist et al. (2013); for Strange Lake (sample SL-146F) from Salvi and Williams-Jones (1996); for Red Mud (sample 14/T/16) from Deady et al. (2016); for Serra Verde (sample SAP) from Santana et al. (2015); for Chinese ion adsorption clays (sample Hua 95-9) from Bao and Zhao (2008). Chondrite normalizing factors from McDonough and Sun (1995).

group, there is a continuum from those intrusions where REE enrichments are largely magmatic, to those where hydrothermal activity has played a major part in REE mineralization. The most significant REE enrichments are associated with intrusions that are not just alkaline, but peralkaline (Dostal 2016). These intrusions, whether undersaturated (nepheline syenites) or oversaturated (peralkaline granites), contain a range of unusual sodic minerals including feldspathoids, sodic amphiboles and sodic pyroxenes. Some of the most REE enriched of the peralkaline intrusions are agpaitic, containing rare Ti- and Zr silicates such as eudialyte and aenigmatite (Marks et al. 2011), and it is in these intrusions where magmatic processes alone can cause REE enrichment.

The only active REE mining in peralkaline igneous rocks takes place in the Lovozero agpaitic nepheline syenite complex, in Russia, where the main ore mineral is loparite (Hedrick et al. 1997; Kogarko et al. 2002). However, many large agpaitic nepheline syenite complexes are currently being explored for the REE: these include Ilímaussaq and Motzfeldt in Greenland, Norra Kärr in Sweden, and Red Wine and Kipawa in Canada (Sørensen 1992; Mariano and Mariano 2012; Goodenough et al. 2016; Dostal 2016). At the majority of these complexes, the ore mineral is eudialyte (and its alteration products (Borst et al. 2016)) although at the Kvanefjeld prospect steenstrupine is the main ore mineral (Sørensen et al. 2011). Agpaitic nepheline syenite deposits may be large in size, but typically have relatively low total rare earth oxide (TREO) grades (generally ≤ 1 wt%). They typically have a much flatter REE pattern than carbonatites and have a negative Eu anomaly (Fig. 5), so that processing for one kg of Nd will also produce good quantities of Dy with less La and Ce. In contrast, these deposits may contain higher than needed concentrations of Y and the HREE (Fig. 6), as confirmed by a recent detailed assessment of advanced REE projects in alkaline rocks against EU

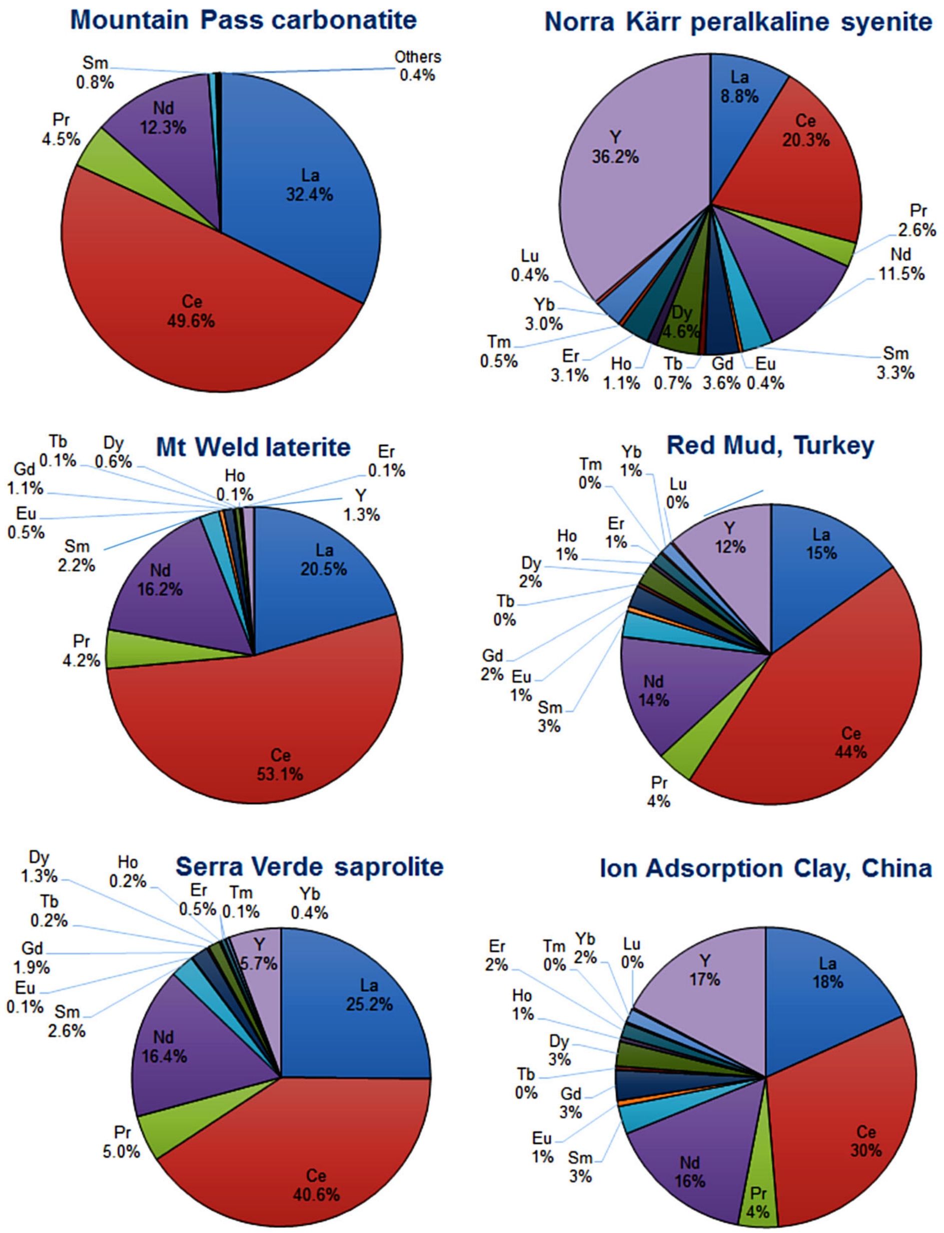

Figure 6. Percentages of individual REE in representative samples from several REE deposits. Data sources as above.

demand (Machacek and Kalvig 2016). Deposits in agpaitic nepheline syenites are also commonly characterized by low Th and U contents, a crucial point for eventual mine development.

Other REE prospects undergoing active exploration occur in peralkaline granites that have been affected by late-stage magmatic fluid activity and hydrothermal alteration. Important deposits include Strange Lake in Canada, Khaldzan-Buregtey in Mongolia, and Bokan Mountain in Alaska (Dostal 2016; Salvi and Williams-Jones 2006). Similar deposits may also occur in alkaline syenitic complexes and felsic volcanic suites that have been affected by late-stage hydrothermal activity. Examples of deposits in syenitic complexes include Thor Lake (Nechalacho) in Canada and Ditrău in Romania (Sheard et al. 2012; Goodenough et al. 2016; Timofeev and Williams-Jones 2015). Key prospects in volcanic rocks are the Brockman and Dubbo Zirconia (Toongi) deposits in Australia (Jaireth et al. 2014; Dostal 2016; Spandler and Morris 2016) and the Round Top deposit in Texas (Jowitt et al. 2017). These magmatic-hydrothermal deposit types most typically show a relatively flat chondrite-normalized REE pattern with a strong negative Eu anomaly, similar to the agpaitic complexes (Fig. 5). The interplay of magmatic and hydrothermal processes means that the ore mineralogy in these deposits can be very variable, with REE-bearing silicates and phosphates such as allanite, zircon, monazite, and xenotime as well as REE carbonates and oxides. This complexity means that grade and tonnage are very varied among deposits of this type, and would add typically significant challenges to separation of ore minerals. Simpler recovery of the REE may be possible where they are concentrated in late-stage or secondary minerals that are easily leachable (Jowitt et al. 2017).

Vein and Skarn Deposits

REE mineralization is, in rare localities, found in vein and skarn systems that do not appear to be intimately associated with alkaline igneous rocks or carbonatites. The most well-known of these are the deposits of the Bastnäs area in Sweden, from where many of the REE were originally identified (Holtstam et al. 2014). Other examples are the high-grade vein-hosted deposits at Steenkampskraal in South Africa and Gakara in Burundi, the origin of which is still not well understood (Harmer and Nex 2016). These deposits are small in tonnage but have high TREO grades, although they are generally LREE dominated. The main ore minerals include bastnäsite and monazite, and Steenkampskraal has ~40% monazite in its main mineralization zone (Harmer and Nex 2016). The high grades, and presence of easily processed minerals, suggest that these deposits may be of significant interest for exploitation, although the monazite ore may be rich in Th that could cause concerns for processing. Whole-rock analyses of this ore are not available for comparison with other deposit types, but Machacek and Kalvig (2016) note that predicted production at Steenkampskraal would be a good match to European Union (EU) demand for Nd, although contents of La, Ce, Pr and Y are low compared to EU demand.

Placers

Placers, or mineral sands, have been sources of REE for some time, most notably at monazite sands in India (Sengupta and Van Gosen 2016) and Australia (Jaireth et al. 2014; Mudd and Jowitt 2016). Placers occur chiefly in coastal and fluvial environments, and are typically formed by erosion of igneous source rocks, although other sources such as volcanic activity are possible, for example, at the Aksu Diamas placer in Turkey (Goodenough et al. 2016). Although placers are most commonly worked for other commodities such as titanium (Ti) or tin (Sn), many have the potential for REE as a by-product. The main ore minerals in many placers are monazite and xenotime; processing routes already exist for both minerals, and both are relatively enriched in the magnet REE Nd, Pr and Dy. Although placers are typically low grade, they have the advantage that beneficiation and recovery of the ore minerals are relatively simple and well-developed (Jordens et al. 2013; Kumari et al. 2015; Krishnamurthy and Gupta 2015). The major restriction on exploitation of placers is the high natural radioactivity due to the presence of Th in monazite and both Th and U in xenotime.

Bauxites

Bauxites are widely mined across the globe for the extraction of aluminum, producing a waste material (red mud) with moderate REE enrichment, of the order of 1000 ppm (Deady et al. 2016). REE patterns are typically flat to mildly LREE enriched (Fig. 5). These bauxites and associated red mud waste products thus have the potential to contain significant REE resources (Wang et al. 2010; Boni et al. 2013; Deady et al. 2016), and research is ongoing to develop processes for extraction of REE (Borra et al. 2015). Although REE grades are low, there would be significant advantage in extracting REE as a by-product of large-scale aluminum production.

Laterites

Thick weathering profiles occur in temperate to tropical zones across the globe, and in tropical areas, these are known as laterites. Where such weathering profiles are developed on igneous or meta-igneous rocks, REE can be remobilized into secondary minerals that accumulate at specific layers within the profile (Berger et al. 2014), and the weathered zones may represent significant REE resources. A classic example of this is the active mine at Mt Weld in Australia, where weathering of a carbonatite has led to the formation of a highly REE-enriched laterite zone up to 70 m thick, which is now covered by later sediments (Jaireth et al. 2014). This laterite zone contains a wide range of REE-bearing secondary phosphate minerals including monazite, churchite and plumbogummite-group minerals (Lottermoser 1990). Other weathered carbonatites that have been subject to substantive exploration programs include Ngualla Hill (Tanzania), Zandkopsdrift (South Africa) and Dong Pao (Vietnam). Enrichment of REE in weathered zones above carbonatites is also known from a few other localities that are of primary interest for niobium; these include the niobium mine at Araxá in Brazil (Verplanck et al. 2016) and the Tomtor and Chuktukon deposits in Russia (Kravchenko and Pokrovsky 1995; Kuzmin et al. 2012). At Tomtor, as at Mt Weld, the weathering zone is enriched in secondary phosphates including secondary monazite (Lazareva et al. 2015). Niobium-bearing lateritic weathering profiles have been described at several African carbonatites including Mrima Hill (Kenya), Panda Hill (Tanzania) and Lueshe (DRC) (Wall et al. 1996; Harmer and Nex 2016); these localities are deserving of further investigation for REE. These laterites are likely to show strong enrichment in the LREE, as at Mt Weld (Figs. 5 and 6), but are of interest because of their high grades.

Ion Adsorption Clays

In a few specific localities, most notably in China, REE in lateritic sections are not held within secondary minerals but are adsorbed onto clay surfaces, from where they can be easily leached at ambient temperatures using a reagent such as ammonium sulfate (Bao and Zhao 2008; Moldoveanu and Papangelakis 2012). Total REE contents are typically low (<4000 ppm) and can vary significantly through the weathering profile, but the relative ease of recovery of REE makes these deposits economically viable (Sanematsu and Watanabe 2016). REE are currently only extracted from ion-adsorption clays in China, where some deposits are relatively enriched in HREE (Bao and Zhao 2008), and they provide the main source for the world's HREE. Ion adsorption-type deposits have been identified in a few other localities, notably at the Serra Verde project in Brazil and the Tantalus project in Madagascar, although not all show the same enrichment in HREE (Moldoveanu and Papangelakis 2016). The distribution of individual REE in some of these ion adsorption-type deposits appears to match most closely to the forecast demand for REE, with good contents of Nd, Pr and Dy (Fig. 6). The controls that underpin development of an ion adsorption clay deposit are not yet well understood, but protoliths in the known localities are typically granitic rocks containing REE minerals that have been affected by deuteric alteration (Sanematsu and Watanabe 2016) or by introduction of REE-enriched carbonate-rich fluids (Xu et al. 2017).

CHALLENGES

With many future uses in green and digital high-technology applications and the recent surge in exploration for REE deposits that has defined plentiful amounts of REE in a variety of geological deposits, why might REE supply in the future be a problem? The answer lies in a combination of technological, economic and geopolitical challenges.

There is a geological challenge in that, compared to other deposit types, relatively little research has been undertaken on REE until the last several years. A wide variety of publications on REE concentration are now appearing, and deposit models are now being refined to permit better targeted exploration; much recent work has been thoroughly reviewed by Verplanck and Hitzman (2016).

Perhaps the more urgent challenge is a better understanding of the mineralogy of REE deposits and associated research to find efficient and environmentally friendly processing methods, especially for those minerals and deposit types that have not been mined before. Very little minerals processing research on REE minerals took place outside of China during the 1980s, 1990s and 2000s. Since then there has been considerable work, with a number of reviews being published and reference texts updated (Gupta and Krishnamurthy 2005; Jordens et al. 2013; Krishnamurthy and Gupta 2015; Moldoveanu and Papangelakis 2016). A summary of the processing considerations associated with the various deposit types is given in Table 1.

Table 1. Challenges in minerals processing for different deposit types

Deposit type	Main minerals	Processing considerations
Carbonatite	Bastnäsite–(Ce) Parisite–(Ce) synchysite–(Ce) Ancylite–(Ce) Monazite–(Ce) REE-bearing apatite [Xenotime–(Y) (rare)]	Properties of minerals other than bastnäsite and monazite not yet well known Carbonatites often intrude as narrow dykes, so likely mixed with fenite (silicate) or earlier carbonatite. Usually subject to sub-solidus alteration producing complex textures, often important in REE enrichment. Gravity, magnetic and flotation beneficiation methods variously used on carbonatite deposits. Acid leaching of impure concentrates expensive because of carbonate content Intrusions open to depth
Agpaitic nepheline syenite	Eudialyte group minerals Steenstrupine Loparite–(Ce)	Variable, complex crystalline textures, with varying degrees of alteration. Igneous textures easier to process than altered assemblages, e.g., REE-bearing eudialyte can be pseudomorphed by a fine-grained assemblage. Multiple possible mineral hosts for REE. Deposits are large albeit with favorable roof zones and igneous layers and some extend to depth
Alkaline granites and syenites, typically hydrothermally altered	Bastnäsite–(Ce) Parisite–(Ce) Synchysite–(Ce) Ancylite–(Ce) Allanite–(Ce) Zircon Fergusonite Monazite–(Ce) Fluorapatite	Variable, complex crystalline textures, with varying degrees of alteration. Multiple possible mineral hosts for REE. Deposits may be very variable in size, shape and distribution of ore minerals. No established processing paths for the main ore minerals
Mineral sand (placer)	Monazite–(Ce) [xenotime–(Y)]	Grains usually separate and well-liberated, suitable for physical processing. REE minerals mostly granite-derived thus contain Th so radioactivity of the concentrate is an issue
Weathered carbonatite	Monazite–(Ce)	Carbonates removed by weathering but often fine-grained with intricate intergrowths and grain coatings, including Fe (hydr)oxides, so, e.g., Mt Weld monazite–(Ce) concentrate produced by flotation rather than the physical beneficiation used for mineral sands. Will vary markedly with depth
Ion adsorption deposit (‘easily leachable deposit’)	Adsorbed cations, not minerals	Leaching used to exchange REE from clays, including in situ leaching, so no crushing/grinding physical or chemical separation. Low grade so can use high amount of chemical reagents. Some REE (up to 50% in deposit defined as ‘ion adsorption’) will be in insoluble minerals, e.g., monazite–(Ce), xenotime–(Y), zircon. Will vary with depth and only part of a profile is amenable to leaching. Some deposits have shallow weathered profile so need large lateral amount of land
Bauxite/red muds	Hydroxyl-bastnäsite–(Nd) Monazite	REE are concentrated in red mud waste following the Bayer process, from where they can be leached

Even for carbonatites, which are currently mined, the mineralogy of the REE varies from carbonatite to carbonatite, so that comprehensive mineralogy, bespoke processing flow sheets and geometallurgy studies are needed for each new project. For example, bastnäsite is the main ore mineral at Bayan Obo and Mountain Pass, along with subsidiary monazite. However, this is not the case in other carbonatite deposits such as Bear Lodge, where ancylite dominates together with monazite and bastnäsite (Mariano and Mariano 2012), or Songwe Hill, where the mineralogy includes synchysite and apatite (Broom-Fendley et al. 2017). Beneficiation of such complex deposits to separate and concentrate the REE ore minerals remains a challenge.

For deposits associated with alkaline igneous rocks, the complexity of the mineralogy leads to significant challenges in processing. As mentioned above, the only current production of REE from this type of deposit is from Lovozero, in Russia, where the ore mineral is loparite (Hedrick et al. 1997; Chakhmouradian and Zaitsev 2012). Eudialyte is the main REE ore mineral in a number of agpaitic nepheline syenite deposits and has not been processed commercially. Although eudialyte has a relatively low total REE content, it has a higher ratio of Nd, Pr and Dy to La and Ce, as well as low U and Th contents, which make it potentially interesting for exploitation. Recent research has investigated options for beneficiation of eudialyte, and for hydrometallurgical methods to recover the REE without formation of silica gel (Stark et al. 2016; Voßenkaul et al. 2016; Davris et al. 2016b). The granitic and syenitic magmatic-hydrothermal deposits, such as Strange Lake, may have the potential to produce good quantities of Nd and Dy without oversupply of La and Ce, but the reality is that their complex mineralogy makes them significantly less attractive in terms of REE beneficiation. In these rock types, the REE may be hosted in a very wide range of minerals, including allanite, zircon, apatite and fergusonite (Table 1) for which there is no established processing route; research into development of processing methods is at an early stage (Jordens et al. 2014).

As a generalization, the low-temperature REE deposits formed by erosion and weathering present fewer challenges in processing than the high-temperature deposits; effectively some of the required work has already been done by nature. Monazite-bearing placers are well known (Sengupta and Van Gosen 2016), and processing methods are established (Kumari et al. 2015). However, placer monazite is typically high in Th, leading to environmental concerns. In contrast, the secondary monazite in the lateritic weathering zone at Mt Weld is relatively low in Th (Jaireth et al. 2014), but despite this the processing plant for Mt Weld concentrate has had to be sited in Malaysia rather than Australia, and has caused significant protests (Ali 2014). In general, though, secondary monazite in weathered carbonatites appears to be a favorable ore mineral for REE processing.

For ion adsorption deposits processing methods are rather simple, involving either in situ or heap leaching of the clays with a chemical cation exchange agent, typically ammonium sulfate. The challenge is that no commercial processing has been done outside of China, where ground clearance and the ammonium sulfate used have caused considerable environmental damage (Yang et al. 2013). It is highly likely that any non-Chinese ion adsorption project would need not only much stricter environmental controls, but possibly also alternative exchange reagents. In situ mining is now encouraged on environmental grounds in China, but comprehensive risk assessments and hydrogeological models would need to be done elsewhere before in situ leaching could take place.

The extraction of REE as by-products from existing mines is potentially an attractive way to bring new supplies rapidly on stream, possibly even ‘switch-on, switch-off’ supplies that could react quickly to changes in demand. The challenge here seems to be to interest the miners of the main commodity to modify their processing routes so that REE can be produced. The additional revenue is often not sufficient to drive changes to established processes, or to encourage recovery of REE from waste products. Innovative business models as well as innovative processes are required. Placers across the globe are mined for commodities such as Ti and zirconium, and in some cases, REE could be a potential by-product, although this is currently avoided in some countries due to concerns about radiation (Mudd and Jowitt 2016). Extraction of REE as a by-product of aluminum production from bauxite appears to have significant potential, particularly as REE are concentrated in the waste red muds, and thus, REE extraction could be separated from the main aluminum recovery. There is much research currently focusing on development of this technology (Borra et al. 2015; Binnemans et al. 2015;

Davris et al. 2016a). Apatite in carbonatites, alkaline rocks and sedimentary phosphorites is mined as a phosphate resource, but there is no widely used industrial method to recover REE from apatite as part of fertilizer production. Research on this subject is ongoing (Al-Thyabat and Zhang 2015; Ogata et al. 2016), and the Acron Group in Russia has developed a process to produce REE from apatite concentrate, with an annual capacity of 200 t REO. The phosphogypsum waste produced during fertilizer production can also represent an important source of REE (Binnemans et al. 2015). Further development of such by-product processing has the potential to be very important for future REE supply.

Gaining the necessary permits to operate including the less tangible 'social license to operate' is a challenge for all mining operations but is a particular difficulty for REE producers if ores contain naturally occurring radioactive minerals and if they will produce radioactive waste. An example is the considerable opposition to Lynas setting up its extraction and separation facility in Malaysia (Ali 2014). In Greenland, a zero-tolerance policy on mining of U and radioactive minerals was repealed by Parliament in 2013, but concerns about the environmental impacts of mining remain (Nuttall 2013). Other environmental concerns include the usual mining problems of water use, waste and waste water management, dust, noise, heavy traffic and social considerations. The REE themselves are not considered to be toxic, although they could be problematic in very high quantities; limited information is available about the toxicity of the individual elements (Pagano et al. 2015). Responsible sourcing is not yet a major issue in REE production, but the required environmental and social standards are only likely to increase.

Development of new REE projects is hindered by the high capital expenditure required to set up some of the planned operations. For example, the alkaline rock projects at Strange Lake and Nechalacho in Canada had capital expenditure estimates in excess of US$ 1 bn (although these may be reduced in future), and Alkane Resources has a capital expenditure estimate of AUS$ 1.3 bn (US$ 979 M) for its Dubbo Zirconia project in Australia with a complex plant that would produce four separate products. In contrast, the Peak Resources carbonatite project at Ngualla, Tanzania, has a capital expenditure cost of US$ 330 M to construct mining, processing and separation facilities in Africa and the UK. To put these figures in context, the current market capitalization for global REE is just US$ 1–2 billion; an order of magnitude less than the value at the peak of REE prices in 2011. So, while these expenditure figures sounded plausible when the market value was high, they are less attractive now. Projects that can start with a low capital expenditure, and then run at low cost, must have a distinct advantage. Projects that are already mining another commodity and can start up extraction of REE as by-products are also well placed.

The large capital expenditure estimates typically include the cost of mining, minerals processing, dissolution and separation of the REE to produce individual rare earth metals. A lower cost development to produce an ore concentrate or intermediate product is difficult because there is almost no supply chain to sell into outside of China. There are few processors except in China, and even fewer that will take a mixed REE product and carry out toll separation. Current examples are Rhodia Solvay, France (which is winding down its involvement in processing ore), Solikamsk Magnesium Works in Russia, the Irtysh Rare Earths Company in Kazakhstan, and possibly NPM Silmet AS, in Estonia. However, using a tolling system is not economic for the majority of producers at current market prices. Again, this option may work best for by-product raw material streams where any cost benefit from selling the material is a bonus.

If no government is prepared to take an interventionist strategy, establishing a supply chain will be a struggle in an environment of low REE prices. Governments have taken a proactive role in encouraging and funding research and development (e.g., the Critical Raw Materials Institute in the USA and the emphasis on critical raw materials in the European Union's Horizon 2020 program) but are reluctant to make direct contributions to mining and processing operations. The importance of REE lies not only in the small amounts used in military applications but also in being able to develop domestic high-technology markets without having to pay premium prices for REE raw materials from China. Neither North America nor Europe currently has a domestic source of REE, despite the presence of several well-known deposits (Mariano and Mariano 2012; Goodenough et al. 2016), and although both continents have well-developed catalyst industries, the phosphor and magnet industries are very strongly focused in China. The major challenge for REE supply outside China is development of the entire value chain, from mining through processing and separation to end-uses.

SUMMARY

We have compared forecast demand for individual REE over the next 10 years against the REE distribution in different REE deposit types. This assessment suggests that the optimum deposit types, in terms of balancing natural concentrations of specific REE against overall projected demand, are the LREE-enriched ion adsorption clays (*not* the most HREE-enriched varieties), and the red muds, based on data plotted here. Ion adsorption clays, together with placers, potentially also have the easiest processing routes for extraction of REE. However, environmental issues can be a concern: placer, laterite and ion-adsorption clay projects potentially have large footprints and can have substantial impacts on local environments and communities. Furthermore, public fear of radioactivity has prevented placer deposits being used as REE resources in most countries.

New mines will need low capital expenditure, reasonable operating costs, low embodied energy and good environmental performance, including the cracking (dissolution) and separation stages. If environmentally friendly reagents and mining methods can be found, our overview suggests that easily leachable deposits such as ion adsorption clays have the highest number of favorable characteristics. Placers are also of interest due to the relative ease of processing, as long as the issue of their natural radioactivity can be successfully managed. REE production as by-products, such as leaching of REE during bauxite processing or removal of REE during phosphate processing for fertilizer, is also of significant interest for future supply. There is certainly a place for the very 'best of the rest' of hard-rock deposit types, including carbonatite-related deposits and alkaline rocks, but there is likely to be diversification of the deposit types that supply future REE resource needs.

Research into all deposit types is still extremely useful because additional knowledge of REE mineralogy, mobility and concentration helps define better exploration models and will produce new exploration targeting suggestions as well as better processing methods. This overview only considers the next 10 years; beyond that time, new technological developments are likely to drive substantial changes in both processing of, and demand for, REE.

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