1 **The rare earth elements: demand, global resources, and challenges for**
2 **resourcing future generations**

3 Kathryn M. Goodenough[1], Frances Wall[2], and David Merriman[3]

4 1: British Geological Survey, the Lyell Centre, Research Avenue South, Edinburgh EH14
5 4AP, UK. kmgo@bgs.ac.uk +44 (0)131 6500272. ORCiD 0000-0001-5912-4831

6 2: Camborne School of Mines and Environment and Sustainability Institute, University of
7 Exeter, Penryn Campus, Penryn, Cornwall TR10 9FE, UK. ORCID: 0000-0002-5393-4400

8

9 3: Roskill Information Services Ltd., 54 Russell Road, London, SW19 1QL, UK

10

11 **Abstract**

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

31 **Keywords**

32 Rare Earth Elements; resources; supply chain; minerals processing

33

34 **Introduction**

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

44 Most recently, some researchers have studied the criticality of individual REE (Du and
45 Graedel 2013; Nassar et al. 2015) and there is increasing awareness that treating them as a
46 single group over-simplifies some of the major issues.

47 In the Earth's crust, there is a general trend of decreasing abundance of REE with increasing
48 atomic number. Superimposed upon this is the 'Oddo-Harkins effect'; elements with an even
49 atomic number are more abundant than those with odd atomic numbers. This means that Ce
50 is the most abundant of the REE in the Earth's crust; in contrast, Lu is genuinely rare. Most
51 natural REE ores are dominated by La, Ce and Nd with much smaller amounts of the HREE.
52 There are many challenges in processing these ores to create the individual metals required
53 by the market, because of the wide range of possible ore minerals that each require a
54 different beneficiation process (Jordens et al. 2013); and because of the additional steps
55 required to separate out each of the individual REE (Xie et al. 2014; Machacek and Fold
56 2014). Almost inevitably, the natural abundance of the different elements in ore does not
57 match market demand, creating the 'balance problem' (Binnemans and Jones 2015). There
58 are several ways to manage the balance problem, including diversification of the resources
59 that are exploited, recycling, substitution of other elements for the REE, and development of
60 new uses for the most abundant REE (Binnemans and Jones 2015). In this paper, we
61 consider how the first of those options might be addressed. We review current and predicted
62 10-year market demand for REE, identifying the most economically-important members of
63 the group. We compare this to known types of natural resources, in order to identify the
64 types of deposits that are likely to be most suitable for future development, and consider the
65 challenges associated with developing these deposits. Recycling of rare earths (the 'urban
66 mine') is not considered in this paper, but has been reviewed elsewhere (Binnemans et al.
67 2013).

68 Changing demand for the rare earth elements

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

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

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

92 show the highest production growth rates in the years to 2026. This production growth is
93 likely to drive greatly increased demand for neodymium-iron-boron (NdFeB) magnets (Fig.
94 2).

95 NdFeB magnets are not unfamiliar to the automotive industry, with most internal combustion
96 engine (ICE) vehicles, HEVs and EVs containing between 40 and 100 small electric motors
97 in components such as windscreen wiper motors and air conditioning systems. However,
98 the on-going electrification of automotives has increased the intensity of use in all vehicle
99 types. NdFeB magnets are used in the powertrain in HEV and EVs as well as for numerous
100 other smaller applications, with up to 2.5 kg of NdFeB magnets being used in the powertrain
101 of current models. In 2016, a total of 5,000 t of NdFeB magnets were estimated to be used
102 in the drive trains of HEV and EVs. The magnets in these powertrains are required to
103 operate under high-temperatures (+150 ^{o}C) whilst retaining a high coercivity, requiring the
104 addition of metals including Dy to the magnet alloys. Though many magnet manufacturers
105 are developing NdFeB magnet alloys with lower Dy contents, automotive power train
106 applications will continue to require higher-Dy content alloys to reliably operate at these
107 higher temperatures (Hao 2016).   As a result, the forecast increase in HEV and EV output
108 will require large volumes of Nd, Pr and Dy.

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

115 Electric vehicles are expected to show the strongest growth in demand, though other
116 applications for NdFeB magnets in renewable energy generation will become increasingly
117 important, as governments and industries make efforts to meet stringent climate change and
118 emissions standards. In 2016, wind turbines were the second largest end-use applications
119 for NdFeB magnets behind consumer electronics, consuming around 8,000 t NdFeB
120 magnets. Global wind capacity is growing rapidly, with the Global Wind Energy Council
121 forecasting cumulative capacity to grow by 12-14%py through to 2020, reaching 790 GW
122 (GWEC 2015). Installed capacity is likely to reach 870 GW in 2021 and could grow to
123 greater than 1,330 GW by 2026 despite slowing growth rates (Fig. 3). China is the largest
124 wind power generator, increasing installed capacity by over 70 GW between 2013 and 2015,
125 though the planned removal of subsidies in 2016 has accelerated the installation of new
126 capacity during this period.

127 Though figures vary by manufacturer and product, the direct-drive permanent magnet
128 generator (DDPMG) design for wind turbines typically requires the largest volumes of NdFeB
129 magnets at 500-700 kg/MW of installed capacity. Hybrid designs use much smaller amounts
130 of NdFeB magnets, typically between 100-200 kg/MW of installed capacity.   Newer DDPMG
131 technologies have become commercially available for large-size turbines, used mainly in off-
132 shore wind farms, which is expected to increase the volume of NdFeB magnets consumed
133 per unit. NdFeB magnets for wind turbines typically contain low or zero Dy in the magnet
134 alloys as the temperature range of operation is controlled by air ventilation. As a result Nd
135 and Pr will be critical to supporting growth in wind turbines using direct drive permanent
136 magnet technologies, though they face a strong substitution threat from ferrite magnets and
137 gearless turbine technologies if REE prices and availability become unfavourable to
138 manufacturers.

139 NdFeB magnet consumption in the years to 2026 will be driven by hybrid and electric
140 vehicles and wind turbines, though the use of these magnets in other applications will
141 support further demand growth. The use of rare earth permanent magnets in motors and
142 sensors of robotic production equipment and machinery is forecast to increase as production
143 lines in major manufacturing nations become more automated. The International Federation
144 of Robotics estimates global production of industrial robots to increase from 290,000 units in
145 2016 to 414,000 units in 2019 (IFoR 2016), largely for use in the automotive,
146 electronics/electrical and metals, chemicals and plastics industries. China is expected to
147 show the highest uptake of industrial robotics, with demand increasing by 21% per year
148 between 2016 and 2019 reaching 160,000 units.

149 Rare earths are often used as additives in glass fibres for fibre optic applications to improve
150 data transfer speeds. Erbium (Er) is the most commonly used dopant with ytterbium (Yb)
151 used in larger scale optical fibres. Other rare earths including thulium (Tm) and Pr have also
152 been used in some optic fibres though these are not commercially produced. Optical fibre
153 cabling for short distance communication has grown globally since 2010, as copper cabling
154 has been replaced in telephone, television and local area network infrastructure to increase
155 data transfer rates. In long distance communication, rare earth doped optical fibres are used
156 in amplifiers, which have been replacing more expensive and less efficient electronic
157 repeaters. Er-doped glass fibre production increased 8-10% per year between 2000 and
158 2016, largely in China. Similar growth rates for erbium glass fibre production are expected in
159 the years to 2026 as higher-speed and larger volume data transfers will be required by both
160 commercial and domestic consumers.

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

176 Lanthanum is used as an additive to improve the refractive index, decrease dispersion and
177 enhance chemical stability in La-series optical lenses, mainly used in wide-angle lenses for
178 consumer electronics. Yttrium and gadolinium (Gd) may be used as a replacement for
179 lanthanum, though their cost premium makes them unattractive substitutes. The increase in
180 production of smartphones and tablets containing optical lenses has seen a surge in
181 demand for La-series glass with production in 2016 reported to total >6,000 t, forecast to
182 increase to >10,000 t in 2020. The development of cerium-iron-boron (CeFeB) magnets in
183 China has been seen as a low-cost alternative to NdFeB magnet materials with less supply
184 availability risk. Though CeFeB magnet alloys are significantly cheaper to produce, they do
185 not have the high-coercivity or temperature range of operation that NdFeB and Dy-NdFeB
186 magnet alloys possess, which many end-use applications require. As a result, CeFeB

187 magnets are likely to be used only in low end products and their production and use outside
188 of China will be limited.

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

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

217 **REE Resources**

218 The majority of the world's REE are still derived from natural (primary) resources, although
219 there is a substantial research and development effort on recycling of REE from manmade
220 (secondary) resources (Binnemans et al. 2013). Natural REE deposits can be divided into a
221 number of different categories on the basis of their geological associations, and various
222 publications have used similar sets of categories (Chakhmouradian and Wall 2012; Wall
223 2014; Goodenough et al. 2016; Verplanck and Hitzman 2016). They include deposits
224 formed by high temperature (magmatic and hydrothermal) processes, typically associated
225 with carbonatites, alkaline igneous rocks, and hydrothermal systems; and deposits formed
226 by low-temperature processes (erosion and weathering) such as placers, bauxites, laterites
227 and ion-adsorption clays. An important aspect of understanding these different deposit
228 types, and considering their potential, is the REE mineralogy (Goodenough and Wall 2016).
229 There are over 100 potential REE ore minerals, but only very few of these have been
230 successfully processed and the REE extracted (Jordens et al. 2013). In the section below we
231 consider each deposit type, the likely mineralogy, and the potential for that deposit type to
232 meet the forecast demand for different REE. For many deposits, bulk analyses of ore divided
233 into the individual REE are not publicly available, so we draw on representative samples
234 from the published literature.

Carbonatites

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

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

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

260 *Alkaline igneous rocks*

261 The second main group of 'hard-rock' REE deposits is normally described as being
262 associated with alkaline silicate igneous rocks, but this encompasses a great deal of
263 variability. Within this group, there is a continuum from those intrusions where REE
264 enrichments are largely magmatic, to those where hydrothermal activity has played a major
265 part in REE mineralisation. The most significant REE enrichments are associated with
266 intrusions that are not just alkaline, but peralkaline (Dostal 2016). These intrusions, whether
267 undersaturated (nepheline syenites) or oversaturated (peralkaline granites) contain a range
268 of unusual sodic minerals including feldspathoids, sodic amphiboles and sodic pyroxenes.
269 Some of the most REE-enriched of the peralkaline intrusions are agpaitic, containing rare Ti-
270 and Zr-silicates such as eudialyte and aenigmatite (Marks et al. 2011), and it is in these
271 intrusions where magmatic processes alone can cause REE enrichment.

272 The only active REE mining in peralkaline igneous rocks takes place in the Lovozero
273 agpaitic nepheline syenite complex, in Russia, where the main ore mineral is loparite
274 (Hedrick et al. 1997; Kogarko et al. 2002). However, many large agpaitic nepheline syenite
275 complexes are currently being explored for the REE: these include Ilímaussaq and Motzfeldt
276 in Greenland, Norra Kärr in Sweden, and Red Wine and Kipawa in Canada (Sørensen 1992;
277 Mariano and Mariano 2012; Goodenough et al. 2016; Dostal 2016). At the majority of these
278 complexes the ore mineral is eudialyte (and its alteration products (Borst et al. 2016))
279 although at the Kvanefjeld prospect steenstrupine is the main ore mineral (Sørensen et al.
280 2011). Agpaitic nepheline syenite deposits may be large in size, but typically have relatively
281 low total rare earth oxide (TREO) grades (generally $\leq$ 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 demand (Machacek and Kalvig 2016). Deposits in agpaitic nepheline syenites are also commonly characterised 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 Ditrãu 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-normalised 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 mineralisation 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 Steenkrampskraal 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 Steenkrampskraal has ~ 40% monazite in its main mineralisation zone (Harmer and Nex 2016). The high grades, and presence of easily processed minerals, suggests 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.

330   2016). Although placers are most commonly worked for other commodities such as titanium
331   (Ti) or tin (Sn), many have the potential for REE as a by-product. The main ore minerals in
332   many placers are monazite and xenotime; processing routes already exist for both minerals,
333   and both are relatively enriched in the magnet REE Nd, Pr and Dy. Although placers are
334   typically low-grade, they have the advantage that beneficiation and recovery of the ore
335   minerals is relatively simple and well-developed (Jordens et al. 2013; Kumari et al. 2015;
336   Krishnamurthy and Gupta 2015). The major restriction on exploitation of placers is the high
337   natural radioactivity due to the presence of Th in monazite and both Th and U in xenotime.

Bauxites

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

Laterites

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

Ion adsorption clays

370   In a few specific localities, most notably in China, REE in lateritic sections are not held within
371   secondary minerals but are adsorbed onto clay surfaces, from where they can be easily
372   leached at ambient temperatures using a reagent such as ammonium sulphate (Bao and
373   Zhao 2008; Moldoveanu and Papangelakis 2012). Total REE contents are typically low
374   (<4000 ppm) and can vary significantly through the weathering profile, but the relative ease
375   of recovery of REE makes these deposits economically viable (Sanematsu and Watanabe
376   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, 90s 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; Moldoveanu and Papangelakis 2016; Krishnamurthy and Gupta 2015). A summary of the processing considerations associated with the various deposit types is given in Table 1.

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

424   interesting for exploitation. Recent research has investigated options for beneficiation of
425   eudialyte, and for hydrometallurgical methods to recover the REE without formation of silica
426   gel (Stark et al. 2016; Davris et al. 2016b; Voßenkaul et al. 2016). The granitic and syenitic
427   magmatic-hydrothermal deposits, such as Strange Lake, may have the potential to produce
428   good quantities of Nd and Dy without oversupply of La and Ce, but the reality is that their
429   complex mineralogy makes them significantly less attractive in terms of REE beneficiation. In
430   these rock-types the REE may be hosted in a very wide range of minerals, including allanite,
431   zircon, apatite and fergusonite (table 1) for which there is no established processing route;
432   research into development of processing methods is at an early stage (Jordens et al. 2014).

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

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

452   The extraction of REE as by-products from existing mines is potentially an attractive way to
453   bring new supplies rapidly on stream, possibly even 'switch-on, switch-off' supplies that
454   could react quickly to changes in demand. The challenge here seems to be to interest the
455   miners of the main commodity to modify their processing routes so that REE can be
456   produced. The additional revenue is often not sufficient to drive changes to established
457   processes, or to encourage recovery of REE from waste products. Innovative business
458   models as well as innovative processes are required. Placers across the globe are mined for
459   commodities such as Ti and zirconium, and in some cases REE could be a potential by-
460   product, although this is currently avoided in some countries due to concerns about radiation
461   (Mudd and Jowitt 2016). Extraction of REE as a by-product of aluminium production from
462   bauxite appears to have significant potential, particularly as REE are concentrated in the
463   waste red muds, and thus REE extraction could be separated from the main aluminium
464   recovery. There is much research currently focusing on development of this technology
465   (Borra et al. 2015; Davris et al. 2016a; Binnemans et al. 2015). Apatite in carbonatites,
466   alkaline rocks and sedimentary phosphorites is mined as a phosphate resource but there is
467   no widely used industrial method to recover REE from apatite as part of fertiliser production.
468   Research on this subject is ongoing (Ogata et al. 2016; Al-Thyabat and Zhang 2015) and the
469   Acron Group in Russia has developed a process to produce REE from apatite concentrate,
470   with an annual capacity of 200 t REO. The phosphogypsum waste produced during fertiliser
471   production can also represent an important source of REE (Binnemans et al. 2015). Further

472 development of such by-product processing has the potential to be very important for future
473 REE supply.

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

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

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

512 If no Government is prepared to take an interventionist strategy, establishing a supply chain
513 will be a struggle in an environment of low REE prices. Governments have taken a proactive
514 role in encouraging and funding research and development (e.g. the Critical Raw Materials
515 Institute in the USA and the emphasis on critical raw materials in the European Union
516 Horizons 2020 programme) but are reluctant to make direct contributions to mining and
517 processing operations. The importance of REE lies not only in the small amounts used in
518 military applications but also in being able to develop domestic high-technology markets
519 without having to pay premium prices for REE raw materials from China. Neither North

520 America nor Europe currently has a domestic source of REE, despite the presence of
521 several well-known deposits (Mariano and Mariano 2012; Goodenough et al. 2016), and
522 although both continents have well-developed catalyst industries, the phosphor and magnet
523 industries are very strongly focused in China. The major challenge for REE supply outside
524 China is development of the entire value chain, from mining through processing and
525 separation to end-uses.

526

Summary

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

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

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

555

556

Acknowledgements

565 Executive Director of the British Geological Survey. The Editor-in-Chief, John Carranza, and
566 two anonymous reviewers are thanked for their positive comments on the initial manuscript.

567 **Figures**

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

569 Figure 2. Forecast production of HEV and EVs versus NdFeB magnet demand, 2010-2026.
570 Data from Roskill (2016b)

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

573 Figure 4. REE market demand by element in 2015 and forecast for 2025. Data from Roskill
574 (2016b)

575 Figure 5. Chondrite-normalised plot showing representative samples from a number of REE
576 deposits. Data for Mountain Pass (sample 11PV01), Bear Lodge (sample GRC-32) and Mt
577 Weld (sample GRC-30) from Verplanck et al. (2016); for Norra Kãrr (sample PGT 407497)
578 from Sjöqvist et al. (2013); for Strange Lake (sample SL-146F) from Salvi and Williams-
579 Jones (1996); for Red Mud (sample 14/T/16) from (Deady et al. 2016); for Serra Verde
580 (sample SAP) from Santana et al. (2015); for Chinese ion adsorption clays (sample Hua 95-
581 9) from (Bao and Zhao 2008). Chondrite normalising factors from McDonough and Sun
582 (1995).

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

585 **Tables**

586 Table 1. Challenges in minerals processing for different deposit types

587

588 **References**

589 Al-Thyabat, S., & Zhang, P. (2015). In-line extraction of REE from Dihydrate (DH) and HemiDihydrate
590   (HDH) wet processes. *Hydrometallurgy, 153*, 30-37,
591   doi:http://dx.doi.org/10.1016/j.hydromet.2015.01.010.
592 Ali, S. (2014). Social and Environmental Impact of the Rare Earth Industries. *Resources, 3*(1), 123.
593 Bao, Z., & Zhao, Z. (2008). Geochemistry of mineralization with exchangeable REY in the weathering
594   crusts of granitic rocks in South China. *Ore Geology Reviews, 33*(3–4), 519-535,
595   doi:http://dx.doi.org/10.1016/j.oregeorev.2007.03.005.
596 Berger, A., Janots, E., Gnos, E., Frei, R., & Bernier, F. (2014). Rare earth element mineralogy and
597   geochemistry in a laterite profile from Madagascar. *Applied Geochemistry, 41*, 218-228.
598 Binnemans, K., & Jones, P. T. (2015). Rare Earths and the Balance Problem. [journal article]. *Journal*
599   *of Sustainable Metallurgy, 1*(1), 29-38, doi:10.1007/s40831-014-0005-1.
600 Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., & Pontikes, Y. (2015). Towards zero-waste
601   valorisation of rare-earth-containing industrial process residues: a critical review. *Journal of*
602   *Cleaner Production, 99*, 17-38, doi:http://dx.doi.org/10.1016/j.jclepro.2015.02.089.
603 Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., et al. (2013). Recycling
604   of rare earths: a critical review. *Journal of Cleaner Production, 51*(0), 1-22,
605   doi:http://dx.doi.org/10.1016/j.jclepro.2012.12.037.
606 Boni, M., Rollinson, G., Mondillo, N., Balassone, G., & Santoro, L. (2013). Quantitative Mineralogical
607   Characterization of Karst Bauxite Deposits in the Southern Apennines, Italy. *Economic*
608   *Geology, 108*(4), 813-833, doi:10.2113/econgeo.108.4.813.

609 Borra, C. R., Pontikes, Y., Binnemans, K., & Van Gerven, T. (2015). Leaching of rare earths from
610   bauxite residue (red mud). *Minerals Engineering, 76*, 20-27,
611   doi:http://dx.doi.org/10.1016/j.mineng.2015.01.005.
612 Borst, A. M., Friis, H., Andersen, T., Nielsen, T. F. D., Waight, T. E., & Smit, M. A. (2016).
613   Zirconosilicates in the kakortokites of the Ilimaussaq complex, South Greenland: implications
614   for fluid evolution and HFSE-REE mineralisation in agpaitic systems. *Mineralogical Magazine*,
615   doi:10.1180/minmag.2016.080.046.
616 Broom-Fendley, S., Brady, A. E., Wall, F., Gunn, G., & Dawes, W. (2017). REE minerals at the Songwe
617   Hill carbonatite, Malawi: HREE-enrichment in late-stage apatite. *Ore Geology Reviews, 81,
618   Part 1*, 23-41, doi:http://dx.doi.org/10.1016/j.oregeorev.2016.10.019.
619 Castor, S. B. (2008). The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks,
620   California. *The Canadian Mineralogist, 46*(4), 779-806, doi:10.3749/canmin.46.4.779.
621 Chakhmouradian, A. R., & Wall, F. (2012). Rare Earth Elements: Minerals, Mines, Magnets (and
622   More). *Elements, 8*, 333-340.
623 Chakhmouradian, A. R., & Zaitsev, A. N. (2012). Rare Earth Mineralization in Igneous Rocks: Sources
624   and Processes. *Elements, 8*, 347-353.
625 Davris, P., Balomenos, E., Panias, D., & Paspaliaris, I. (2016a). Selective leaching of rare earth
626   elements from bauxite residue (red mud), using a functionalized hydrophobic ionic liquid.
627   *Hydrometallurgy, 164*, 125-135.
628 Davris, P., Stopic, S., Balomenos, E., Panias, D., Paspaliaris, I., & Friedrich, B. (2016b). Leaching of rare
629   earth elements from eudialyte concentrate by suppressing silica gel formation. *Minerals
630   Engineering*.
631 Deady, É. A., Mouchos, E., Goodenough, K., Williamson, B. J., & Wall, F. (2016). A review of the
632   potential for rare-earth element resources from European red muds: examples from
633   Seydişehir, Turkey and Parnassus-Giona, Greece. *Mineralogical Magazine, 80*(1), 43-61.
634 Dostal, J. (2016). Rare Metal Deposits Associated with Alkaline/Peralkaline Igneous Rocks. In P.
635   Verplanck, & M. Hitzman (Eds.), *Rare Earth and Critical Elements in Ore Deposits* (Vol.
636   Reviews in Economic Geology 18, pp. 33-54). Littleton, Colorado: Society of Economic
637   Geologists.
638 Du, X., & Graedel, T. E. (2013). Uncovering the end uses of the rare earth elements. *Science of The
639   Total Environment, 461–462*(0), 781-784,
640   doi:http://dx.doi.org/10.1016/j.scitotenv.2013.02.099.
641 EC (2014). Report on Critical Raw Materials for the EU.
642 Goodenough, K. M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., et al. (2016). Europe's
643   rare earth element resource potential: An overview of REE metallogenetic provinces and
644   their geodynamic setting. *Ore Geology Reviews, 72, Part 1*, 838-856,
645   doi:http://dx.doi.org/10.1016/j.oregeorev.2015.09.019.
646 Goodenough, K. M., & Wall, F. (2016). Critical Metal Mineralogy: Preface to the special issue of
647   Mineralogical Magazine. *Mineralogical Magazine, 80*(1), 1-4,
648   doi:10.1180/minmag.2016.080.000.
649 Gupta, C. K., & Krishnamurthy, N. (2005). *Extractive Metallurgy of Rare Earths*: CRC Press.
650 GWEC (2015). Global Wind Report: Annual Market Update.
651 Hao, Z. (2016). *Developments in Dysprosium & Terbium Free Rare Earth Magnets.* Paper presented at
652   the 12th International Rare Earths Conference, Hong Kong,
653 Harmer, R., & Nex, P. (2016). Rare Earth Deposits of Africa. *Episodes, 39*(2), 381-406.
654 Hedrick, J. B., Sinha, S. P., & Kosynkin, V. D. (1997). Loparite, a rare-earth ore (Ce, Na, Sr, Ca)(Ti, Nb,
655   Ta, Fe+3)O3. *Journal of Alloys and Compounds, 250*(1–2), 467-470,
656   doi:http://dx.doi.org/10.1016/S0925-8388(96)02824-1.
657 Holtstam, D., Andersson, U. B., Broman, C., & Mansfeld, J. (2014). Origin of REE mineralization in the
658   Bastnäs-type Fe-REE-(Cu-Mo-Bi-Au) deposits, Bergslagen, Sweden. *Mineralium Deposita*,
659   933-966, doi:10.1007/s00126-014-0553-0.

660 IFoR (2016). World Robotics 2016 Industrial Robots.

661 Jaireth, S., Hoatson, D. M., & Miezitis, Y. (2014). Geological setting and resources of the major rare-
662   earth-element deposits in Australia. *Ore Geology Reviews, 62*, 72-128,
663   doi:http://dx.doi.org/10.1016/j.oregeorev.2014.02.008.

664 Jordens, A., Cheng, Y. P., & Waters, K. E. (2013). A review of the beneficiation of rare earth element
665   bearing minerals. *Minerals Engineering, 41*(0), 97-114,
666   doi:http://dx.doi.org/10.1016/j.mineng.2012.10.017.

667 Jordens, A., Sheridan, R. S., Rowson, N. A., & Waters, K. E. (2014). Processing a rare earth mineral
668   deposit using gravity and magnetic separation. *Minerals Engineering, 62*, 9-18,
669   doi:http://dx.doi.org/10.1016/j.mineng.2013.09.011.

670 Jowitt, S. M., Medlin, C. C., & Cas, R. A. F. (2017). The rare earth element (REE) mineralisation
671   potential of highly fractionated rhyolites: A potential low-grade, bulk tonnage source of
672   critical metals. *Ore Geology Reviews, 86*, 548-562,
673   doi:http://dx.doi.org/10.1016/j.oregeorev.2017.02.027.

674 Kogarko, L. N., Williams, C. T., & Woolley, A. R. (2002). Chemical evolution and petrogenetic
675   implications of loparite in the layered, agpaitic Lovozero complex, Kola Peninsula, Russia.
676   *Mineralogy and Petrology, 74*(1), 1-24, doi:10.1007/s710-002-8213-2.

677 Kravchenko, S., & Pokrovsky, B. (1995). The Tomtor alkaline ultrabasic massif and related REE-Nb
678   deposits, northern Siberia. *Economic Geology, 90*(3), 676-689.

679 Krishnamurthy, N., & Gupta, C. K. (2015). *Extractive Metallurgy of Rare Earths, Second Edition*: CRC
680   Press.

681 Kumari, A., Panda, R., Jha, M. K., Kumar, J. R., & Lee, J. Y. (2015). Process development to recover
682   rare earth metals from monazite mineral: A review. *Minerals Engineering, 79*, 102-115,
683   doi:http://dx.doi.org/10.1016/j.mineng.2015.05.003.

684 Kuzmin, V. I., Pashkov, G. L., Lomaev, V. G., Voskresenskaya, E. N., & Kuzmina, V. N. (2012).
685   Combined approaches for comprehensive processing of rare earth metal ores.
686   *Hydrometallurgy, 129–130*, 1-6, doi:http://dx.doi.org/10.1016/j.hydromet.2012.06.011.

687 Kynicky, J., Smith, M. P., & Xu, C. (2012). Diversity of Rare Earth Deposits: The Key Example of China.
688   *Elements, 8*(5), 361-367, doi:10.2113/gselements.8.5.361.

689 Lazareva, E. V., Zhmodik, S. M., Dobretsov, N. L., Tolstov, A. V., Shcherbov, B. L., Karmanov, N. S., et
690   al. (2015). Main minerals of abnormally high-grade ores of the Tomtor deposit (Arctic
691   Siberia). *Russian Geology and Geophysics, 56*(6), 844-873,
692   doi:http://dx.doi.org/10.1016/j.rgg.2015.05.003.

693 Li, M., Duan, C., Wang, H., Liu, Z., Wang, M., & Hu, Y. (2016). Lanthanum histidine with
694   pentaerythritol and zinc stearate as thermal stabilizers for poly(vinyl chloride). *Journal of
695   Applied Polymer Science, 133*(3), n/a-n/a, doi:10.1002/app.42878.

696 Li, M., Jiang, Z., Liu, Z., Hu, Y., Wang, M., & Wang, H. (2013). Effect of lanthanum cyanurate as novel
697   organic thermal stabilizers for polyvinyl chloride. *Polymer Engineering & Science, 53*(8),
698   1706-1711, doi:10.1002/pen.23419.

699 Lottermoser, B. G. (1990). Rare-earth element mineralisation within the Mt. Weld carbonatite
700   laterite, Western Australia. *Lithos, 24*(2), 151-167, doi:http://dx.doi.org/10.1016/0024-
701   4937(90)90022-S.

702 Machacek, E., & Fold, N. (2014). Alternative value chains for rare earths: The Anglo-deposit
703   developers. *Resources Policy, 42*, 53-64,
704   doi:http://dx.doi.org/10.1016/j.resourpol.2014.09.003.

705 Machacek, E., & Kalvig, P. (2016). Assessing advanced rare earth element-bearing deposits for
706   industrial demand in the EU. *Resources Policy, 49*, 186-203,
707   doi:http://dx.doi.org/10.1016/j.resourpol.2016.05.004.

708 Mariano, A. N., & Mariano, A. (2012). Rare Earth Mining and Exploration in North America. *Elements,
709   8*(5), 369-376, doi:10.2113/gselements.8.5.369.

Marks, M. A. W., Hettmann, K., Schilling, J., Frost, B. R., & Markl, G. (2011). The Mineralogical Diversity of Alkaline Igneous Rocks: Critical Factors for the Transition from Miaskitic to Agpaitic Phase Assemblages. *Journal of Petrology, 52*(3), 439-455, doi:10.1093/petrology/egq086.

Massari, S., & Ruberti, M. (2013). Rare earth elements as critical raw materials: Focus on international markets and future strategies. *Resources Policy, 38*(1), 36-43, doi:http://dx.doi.org/10.1016/j.resourpol.2012.07.001.

McDonough, W. F., & Sun, S.-s. (1995). The Composition of the Earth. *Chemical Geology, 120*, 223-253.

Moldoveanu, G. A., & Papangelakis, V. G. (2012). Recovery of rare earth elements adsorbed on clay minerals: I. Desorption mechanism. *Hydrometallurgy, 117–118*, 71-78, doi:http://dx.doi.org/10.1016/j.hydromet.2012.02.007.

Moldoveanu, G. A., & Papangelakis, V. G. (2016). An overview of rare-earth recovery by ion-exchange leaching from ion-adsorption clays of various origins. *Mineralogical Magazine, 80*(1), 63-76.

Mudd, G. M., & Jowitt, S. M. (2016). Rare earth elements from heavy mineral sands: assessing the potential of a forgotten resource. *Applied Earth Science, 125*(3), 107-113, doi:10.1080/03717453.2016.1194955.

Nassar, N. T., Du, X., & Graedel, T. E. (2015). Criticality of the Rare Earth Elements. *Journal of Industrial Ecology, 19*(6), 1044-1054, doi:10.1111/jiec.12237.

Nuttall, M. (2013). Zero-tolerance, uranium and Greenland's mining future. *The Polar Journal, 3*(2), 368-383, doi:10.1080/2154896X.2013.868089.

Ogata, T., Narita, H., Tanaka, M., Hoshino, M., Kon, Y., & Watanabe, Y. (2016). Selective recovery of heavy rare earth elements from apatite with an adsorbent bearing immobilized tridentate amido ligands. *Separation and Purification Technology, 159*, 157-160, doi:http://dx.doi.org/10.1016/j.seppur.2016.01.008.

Pagano, G., Guida, M., Tommasi, F., & Oral, R. (2015). Health effects and toxicity mechanisms of rare earth elements—Knowledge gaps and research prospects. *Ecotoxicology and Environmental Safety, 115*, 40-48, doi:http://dx.doi.org/10.1016/j.ecoenv.2015.01.030.

Riba, J.-R., López-Torres, C., Romeral, L., & Garcia, A. (2016). Rare-earth-free propulsion motors for electric vehicles: A technology review. *Renewable and Sustainable Energy Reviews, 57*, 367-379, doi:http://dx.doi.org/10.1016/j.rser.2015.12.121.

Roskill (2016a). Lithium: Global industry, Markets and Outlook, 13th edition.

Roskill (2016b). Rare Earths: Global Industry, Markets and Outlook, 16th Edition.

Salvi, S., & Williams-Jones, A. E. (1996). The role of hydrothermal processes in concentrating high-field strength elements in the Strange Lake peralkaline complex, northeastern Canada. *Geochimica et Cosmochimica Acta, 60*(11), 1917-1932.

Salvi, S., & Williams-Jones, A. E. (2006). Alteration, HFSE mineralisation and hydrocarbon formation in peralkaline igneous systems: Insights from the Strange Lake Pluton, Canada. *Lithos, 91*(1–4), 19-34, doi:http://dx.doi.org/10.1016/j.lithos.2006.03.040.

Sanematsu, K., & Watanabe, Y. (2016). Characteristics and Genesis of Ion Adsorption-Type Rare Earth Element Deposits In P. Verplanck, & M. Hitzman (Eds.), *Rare Earth and Critical Elements in Ore Deposits* (Vol. Reviews in Economic Geology 18, pp. 55-79). Littleton, Colorado: Society of Economic Geologists.

Santana, I. V., Wall, F., & Botelho, N. F. (2015). Occurrence and behavior of monazite-(Ce) and xenotime-(Y) in detrital and saprolitic environments related to the Serra Dourada granite, Goiás/Tocantins State, Brazil: Potential for REE deposits. *Journal of Geochemical Exploration, 155*, 1-13.

Sengupta, D., & Van Gosen, B. S. (2016). Placer-Type Rare Earth Element Deposits. In P. Verplanck, & M. Hitzman (Eds.), *Rare Earth and Critical Elements in Ore Deposits* (Vol. Reviews in Economic Geology 18, pp. 81-100). Littleton, Colorado: Society of Economic Geologists.

Seredin, V. V. (2010). A new method for primary evaluation of the outlook for rare earth element ores. [journal article]. *Geology of Ore Deposits, 52*(5), 428-433, doi:10.1134/s1075701510050077.

Sheard, E. R., Williams-Jones, A. E., Heiligmann, M., Pederson, C., & Trueman, D. L. (2012). Controls on the Concentration of Zirconium, Niobium, and the Rare Earth Elements in the Thor Lake Rare Metal Deposit, Northwest Territories, Canada. *Economic Geology, 107*, 81-104.

Sjöqvist, A. S. L., Cornell, D. H., Andersen, T., Erambert, M., Ek, M., & Leijd, M. (2013). Three Compositional Varieties of Rare-Earth Element Ore: Eudialyte-Group Minerals from the Norra Kärr Alkaline Complex, Southern Sweden. *Minerals, 3*, 94-120, doi:10.3390/min3010094.

Smith, M. P., Campbell, L. S., & Kynicky, J. (2015). A review of the genesis of the world class Bayan Obo Fe–REE–Nb deposits, Inner Mongolia, China: Multistage processes and outstanding questions. *Ore Geology Reviews, 64*, 459-476, doi:http://dx.doi.org/10.1016/j.oregeorev.2014.03.007.

Smith, M. P., Moore, K., Kavecsánszki, D., Finch, A. A., Kynicky, J., & Wall, F. (2016). From mantle to critical zone: A review of large and giant sized deposits of the rare earth elements. *Geoscience Frontiers, 7*(3), 315-334, doi:http://dx.doi.org/10.1016/j.gsf.2015.12.006.

Smith Stegen, K. (2015). Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis. *Energy Policy, 79*, 1-8, doi:http://dx.doi.org/10.1016/j.enpol.2014.12.015.

Sørensen, H. (1992). Agpaitic nepheline syenites: a potential source of rare elements. *Applied Geochemistry, 7*(5), 417-427, doi:http://dx.doi.org/10.1016/0883-2927(92)90003-L.

Sørensen, H., Bailey, J. C., & Rose-Hansen, J. (2011). The emplacement and crystallization of the U–Th–REE rich agpaitic and hyperagpaitic lujavrites at Kvanefjeld, Ilímaussaq alkaline complex, South Greenland. *Bulletin of the Geological Society of Denmark, 59*, 69-92.

Spandler, C., & Morris, C. (2016). Geology and genesis of the Toongi rare metal (Zr, Hf, Nb, Ta, Y and REE) deposit, NSW, Australia, and implications for rare metal mineralization in peralkaline igneous rocks. [journal article]. *Contributions to Mineralogy and Petrology, 171*(12), 104, doi:10.1007/s00410-016-1316-y.

Stark, T., Silin, I., & Wotruba, H. (2016). Mineral Processing of Eudialyte Ore from Norra Kärr. [journal article]. *Journal of Sustainable Metallurgy*, 1-7, doi:10.1007/s40831-016-0073-5.

Timofeev, A., & Williams-Jones, A. E. (2015). The Origin of Niobium and Tantalum Mineralization in the Nechalacho REE Deposit, NWT, Canada. *Economic Geology, 110*(7), 1719-1735, doi:10.2113/econgeo.110.7.1719.

Verplanck, P. L., & Hitzman, M. (2016). *Rare earth and Critical Elements in Ore Deposits* (Vol. Reviews in Economic Geology Vol 18). Littleton, Colorado: Society of Economic Geologists.

Verplanck, P. L., Mariano, A. N., & Mariano, A. (2016). Rare earth element ore geology of carbonatites. In P. Verplanck, & M. Hitzman (Eds.), *Rare Earth and Critical Elements in Ore Deposits* (Vol. Reviews in Economic Geology 18, pp. 5-32). Littleton, Colorado: Society of Economic Geologists

Voßenkaul, D., Birich, A., Müller, N., Stoltz, N., & Friedrich, B. (2016). Hydrometallurgical processing of eudialyte bearing concentrates to recover rare earth elements via low-temperature dry digestion to prevent the silica gel formation. *Journal of Sustainable Metallurgy*, 1-11.

Wall, F. (2014). Rare earth elements. In A. G. Gunn (Ed.), *Critical Metals Handbook* (pp. 312-339): John Wiley & Sons.
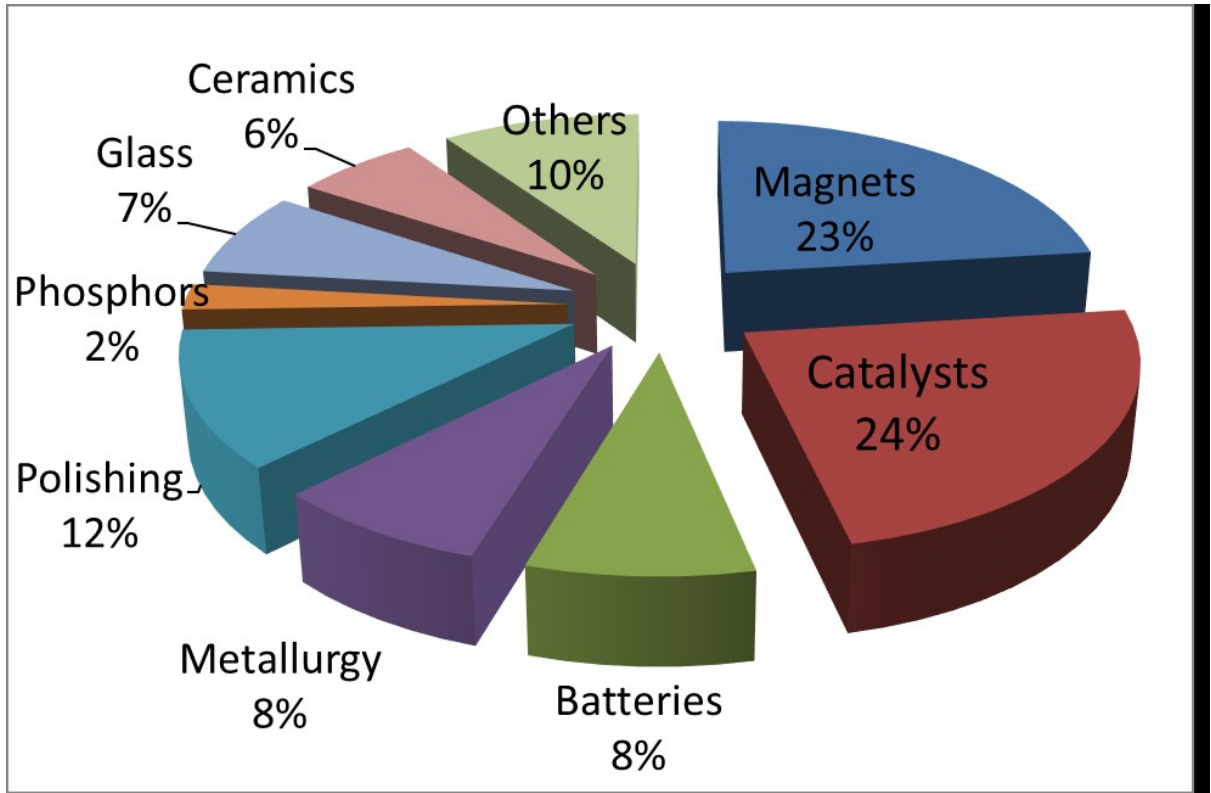
Wall, F., & Mariano, A. N. (1996). Rare earth minerals in carbonatites: a discussion centred on the Kangankunde Carbonatite, Malawi. In A. P. Jones, F. Wall, & C. T. Williams (Eds.), *Rare Earth Minerals: Chemistry, origin and ore deposits* (pp. 193-226): Chapman and Hall.

Wall, F., Williams, C., Woolley, A., & Nasraoui, M. (1996). Pyrochlore from weathered carbonatite at Lueshe, Zaire. *Mineralogical Magazine, 60*(5), 731-750.

810 Wang, Q., Deng, J., Liu, X., Zhang, Q., Sun, S., Jiang, C., et al. (2010). Discovery of the REE minerals
811   and its geological significance in the Quyang bauxite deposit, West Guangxi, China. *Journal of*
812   *Asian Earth Sciences, 39*(6), 701-712, doi:http://dx.doi.org/10.1016/j.jseaes.2010.05.005.
813 Xie, F., Zhang, T. A., Dreisinger, D., & Doyle, F. (2014). A critical review on solvent extraction of rare
814   earths from aqueous solutions. *Minerals Engineering, 56*, 10-28,
815   doi:http://dx.doi.org/10.1016/j.mineng.2013.10.021.
816 Xu, C., Kynický, J., Smith, M. P., Kopriva, A., Brtnický, M., Urubek, T., et al. (2017). Origin of heavy
817   rare earth mineralization in South China. [Article]. *Nature Communications, 8*, 14598,
818   doi:10.1038/ncomms14598.
819 Yang, X. J., Lin, A., Li, X.-L., Wu, Y., Zhou, W., & Chen, Z. (2013). China's ion-adsorption rare earth
820   resources, mining consequences and preservation. *Environmental Development, 8*, 131-136,
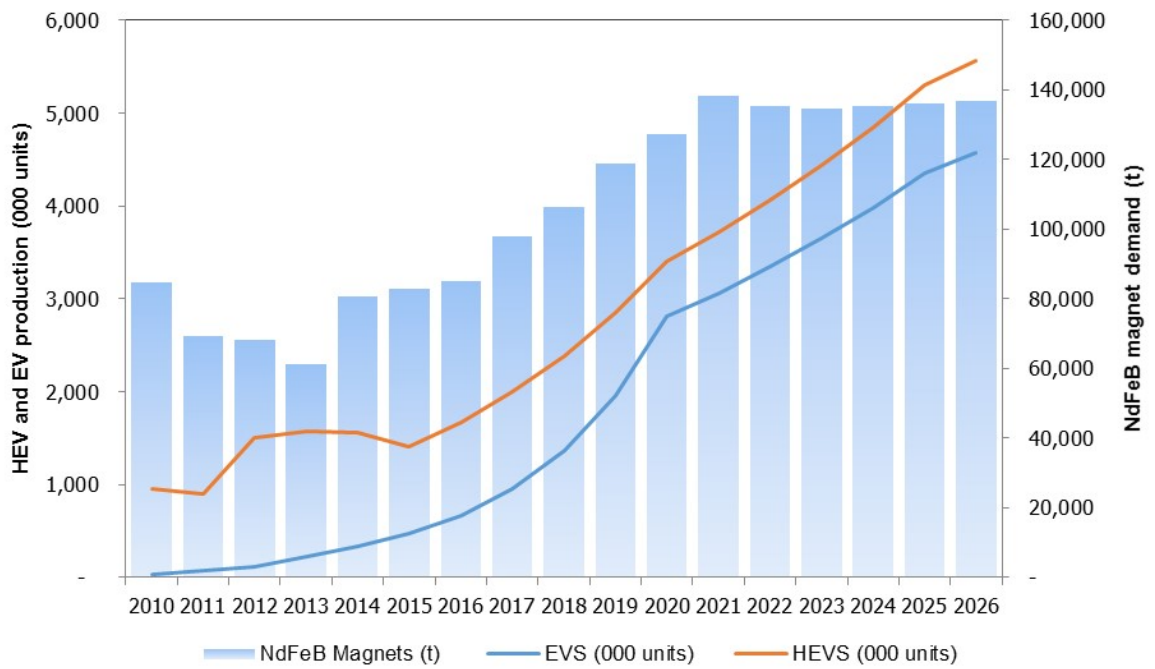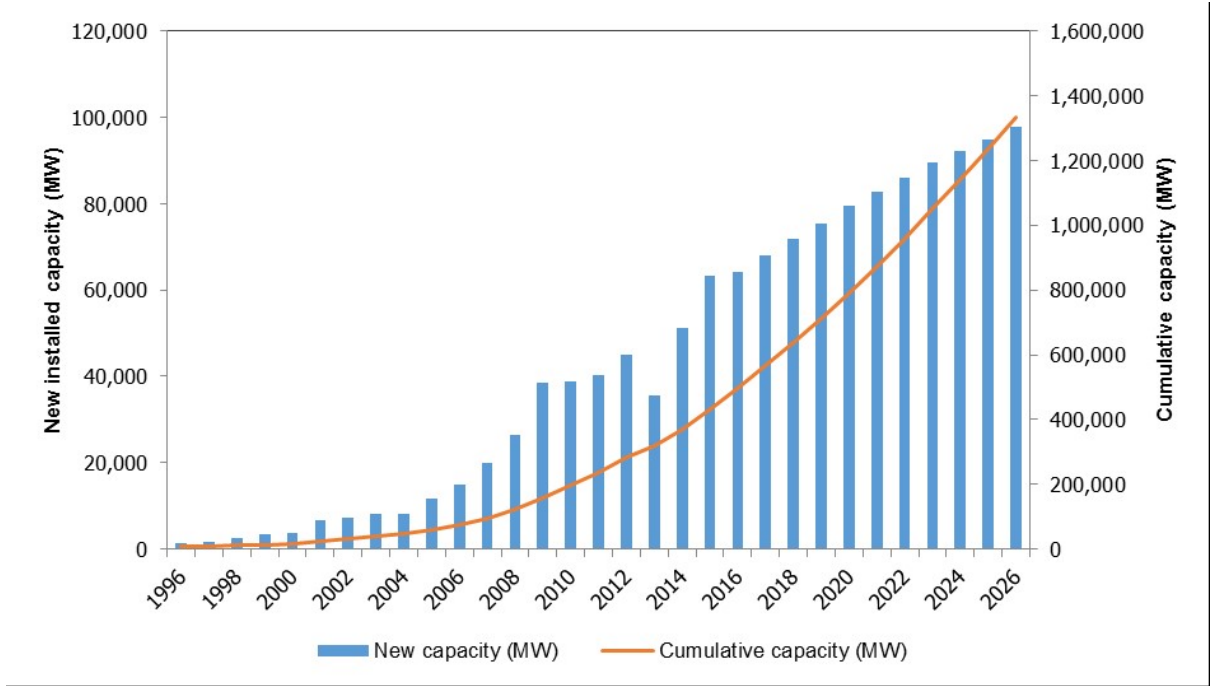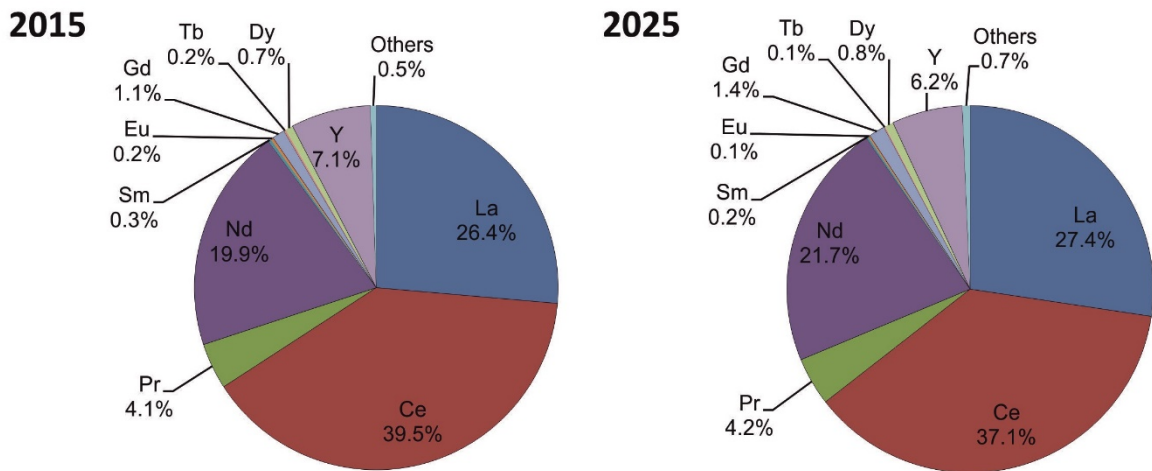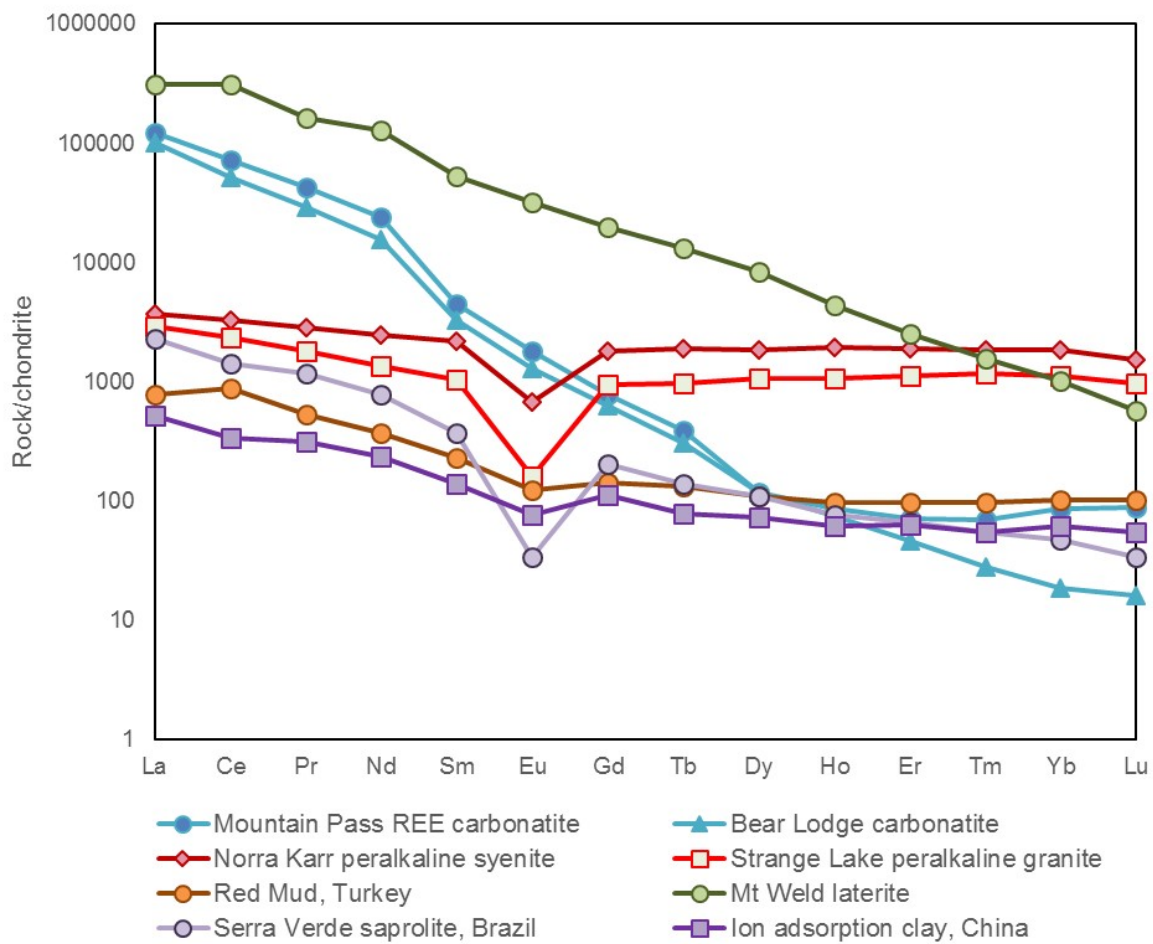821   doi:http://dx.doi.org/10.1016/j.envdev.2013.03.006.

822

823

824

825   Fig. 1
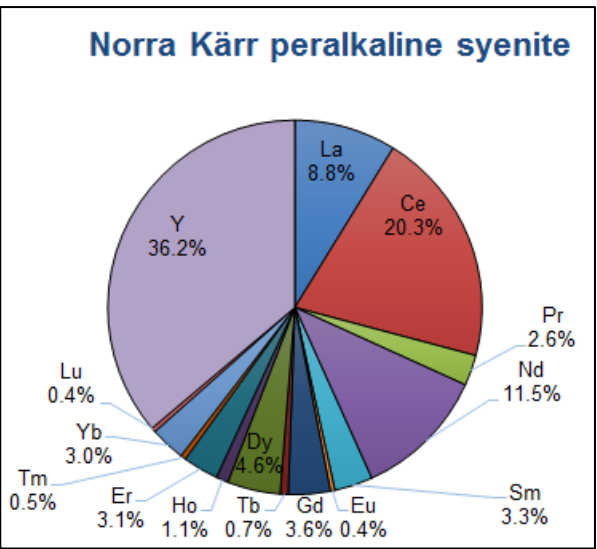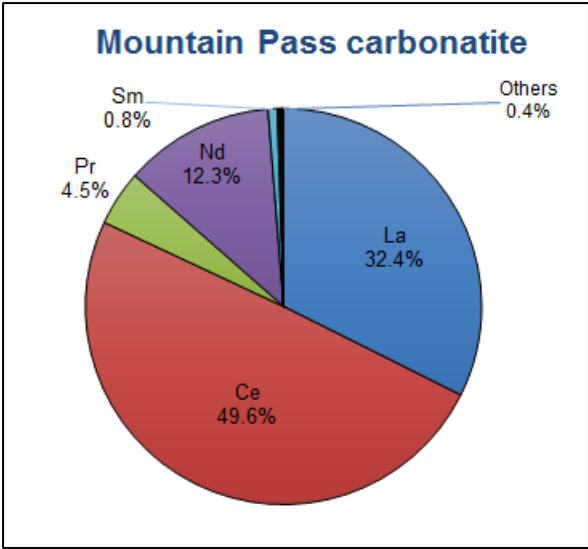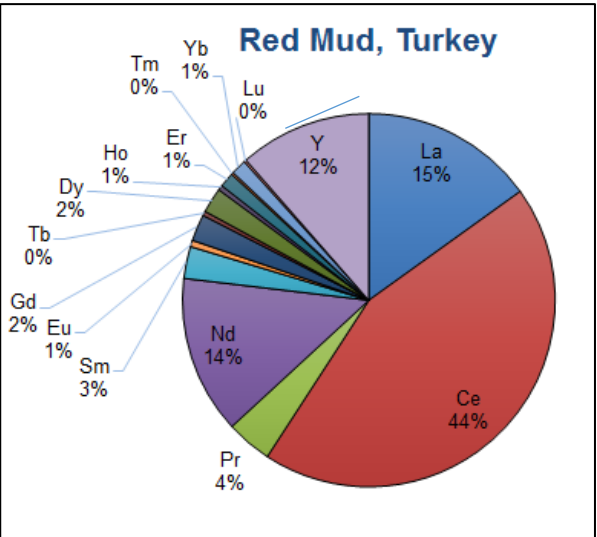

826

827   Fig. 2

828

829   Fig. 3

830

831   Fig. 4

832

833   Fig. 5

834

Mountain Pass carbonatite
Sm 0.8%, Others 0.4%, Pr 4.5%, Nd 12.3%, La 32.4%, Ce 49.6%

Norra Kärr peralkaline syenite
La 8.8%, Ce 20.3%, Y 36.2%, Pr 2.6%, Nd 11.5%, Lu 0.4%, Yb 3.0%, Tm 0.5%, Er 3.1%, Ho 1.1%, Tb 0.7%, Dy 4.6%, Gd 3.6%, Eu 0.4%, Sm 3.3%

Mt Weld laterite
Tb 0.1%, Dy 0.6%, Gd 1.1%, Eu 0.5%, Sm 2.2%, Ho 0.1%, Er 0.1%, Y 1.3%, La 20.5%, Nd 16.2%, Pr 4.2%, Ce 53.1%

Red Mud, Turkey
Tm 0%, Yb 1%, Lu 0%, Ho 1%, Er 1%, Y 12%, La 15%, Dy 2%, Tb 0%, Gd 2%, Eu 1%, Sm 3%, Nd 14%, Pr 4%, Ce 44%

Serra Verde saprolite
Dy 1.3%, Ho 0.2%, Er 0.5%, Tm 0.1%, Yb 0.4%, Tb 0.2%, Gd 1.9%, Eu 0.1%, Sm 2.6%, Y 5.7%, La 25.2%, Nd 16.4%, Pr 5.0%, Ce 40.6%

Ion Adsorption Clay, China
Er 2%, Tm 0%, Yb 2%, Lu 0%, Ho 1%, Dy 3%, Tb 0%, Gd 3%, Eu 1%, Sm 3%, Y 17%, La 18%, Nd 16%, Pr 4%, Ce 30%

Fig. 6

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 favourable 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.

840

841