Responsible Sourcing of Critical Metals

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ABSTRACT

Most critical raw materials, such as the rare earth elements (REE), are starting products in long manufacturing supply chains. It is difficult for consumers, buying cars or smartphones for example, to engage with the original mines and demand environmental and social best practice. Geoscientists can become involved in responsible sourcing because geology is related to environmental impact factors such as energy requirements, resource efficiency, radioactivity and the amount of rock mined. The energy and material inputs and emissions and waste from mining and processing can be quantified using life cycle assessment (LCA). Preliminary LCA studies for REE show little over all difference between 'hard rocks' such as carbonatites and easily leachable ion adsorption clays, mainly because of the embodied energy in chemicals used for leaching, dissolution and separation.

Keywords: responsible sourcing, critical metals, rare earths, life cycle assessment

INTRODUCTION

Current technologies use a wider range of elements than ever before. The manufacture of a computer chip demands 44 different elements (Graedel et al. 2015). Touch screens need a thin film of indium tin oxide, capacitors in electronics contain tantalum, permanent magnets, ranging from the tiny speakers in smartphones to tonnes in large wind turbines, are made of NdFeB. Lithium ion batteries, containing also cobalt and graphite, are widespread and increasing in use rapidly. Despite the many uses of some of these elements, the amounts needed worldwide are often only in the tens to thousands of tonnes per year, orders of magnitude less than those of mainstream commodities such as copper. This means that just a few mines can be sufficient for supply and thus the choice of source is limited. For some

commodities such as indium, there are no mines, and smelter by-products are the only source. Recycling rates are often low. The potential supply risk is high, and such elements are called 'critical', criticality being usually calculated from a combination of the economic importance of the raw materials, the difficulty of substituting another raw material, and the supply risk (European Commission 2014; British Geological Survey 2015; Graedel et al. 2015).

Since many of these critical metals are used in technologies that improve our care of the Earth's environment, it seems appropriate to try to ensure that their production does not itself harm the environment, nor the local communities and people that produce them. Responsible mining is about minimising the negative effects of mining and maximising the positive outcomes (e.g. Goodland 2012). It considers environmental protection, community interaction, workforce health and safety, transparency in economic contributions such as taxes, and also energy use, carbon footprint, water use, resource efficiency, and resource and reserve reporting. Responsible sourcing is about all of these issues and how we can be assured as final consumers that the supply chains, including the ultimate sources, for our goods meet acceptable standards. Responsible sourcing was noted as a key stakeholder requirement of the mining industry in the seminal Breaking New Ground: Mining, Minerals and Sustainable Development report (IIED 2002) and again more recently by multinational mining companies (ICMM 2015).

In this article, we consider the issues involved in critical raw materials, using the example of rare earth elements (REE), and draw attention to the challenges relevant to geoscientists.

RESPONSIBLE MINING AND SOURCING SCHEMES

Most mining companies seek to demonstrate their commitment to responsible mining practices. In order to be able to distinguish 'window dressing' from effective and comprehensive action, however, some kind of assurance is required. Examples include the Global Reporting Initiative used by multinational companies in the ICMM (www.icmm.com), and the Responsible Jewellery Council scheme (www.responsiblejewellery.com). Some schemes for gold and gemstones, such as Fairmined (www.fairmined.org) are similar to the well-known fair trade schemes for tea and coffee. To date only a few raw materials, such as the conflict mineral, 'coltan' (main ore of Ta) are covered under legally binding social regulations. Manufacturers who have attempted to understand their supply chain and connect consumers with raw materials include Fairphone, which has designed its product around the need for conflict-free metals. For most complex

products though, it is hard for the consumer to make a connection to the mines that produced the raw materials. The main drivers for responsible mining of most critical metals are not yet responsible sourcing initiatives from consumers but the need for mining companies to (1) satisfy investment banks in order to raise capital, (2) gain informal approval (social licence to operate) from their host communities and (3) comply with the laws of the countries in which they operate. These drivers and controls all apply to critical metals mines as well as to the production of mainstream commodities. There are so many different management and reporting systems that it is still difficult to identify any clear 'responsible mined' mark that could penetrate and influence the long supply chains in which critical metals are normally involved.

RARE EARTH SUPPLY

An introduction to REE has been given in a previous Elements volume edited by Chakhmouradian and Wall (2012). Other reviews of REE as critical metals are given in Wall (2014) and Verplanck and Hitzman (2016). As mentioned above, the REE (the term is used here to include 15 elements: Y, La – Lu without Pm which has no long-lived isotope) are essential in many technologies owing to their magnetic, redox and luminescent properties. They are classed as critical because supply is dominated by just one country, China. Prices for REE rose dramatically in 2010 and 2011, when China threatened to cut supply quotas, but more recently the supply situation has eased and prices have now dropped back to 2010 levels. A complication of REE deposits is the propensity of the REE to follow one another geochemically, such that there are no ore deposits of individual members of the REE series. Although some geological processes fractionate the light REE from the heavy REE (Chakhmouradian and Wall 2012) all members of the series occur together.

The production of REE usually follows conventional mining techniques, with open pit mines, followed by comminution (crushing and grinding) of the ore, separation of the ore from waste by physical methods such as gravity and magnetic separation, or by froth flotation or a combination of the two (Figure 1). The REE minerals then need to be dissolved ('cracked') to release the REE. An intermediate mixed REE carbonate or oxalate can be shipped at this stage. The next step, required in all cases, is further processing to separate the REE from each other which is the most important step in adding value, and leads to high purity REE metals and oxides that are sold to manufacturing industry (Figure 1).

By far the largest mine is in altered and metamorphosed carbonatite at Bayan Obo, Inner Mongolia, China with smaller carbonate/alkaline rock and carbonatite mines at Weishan, Shandong, and Maoniuping/Dalucao, Sichuan, for 'light' REE (La-Sm). All are open cast quarries. The higher atomic number, 'heavy' REE (Eu-Lu) come mainly from about 200 small mines working 'ion adsorption clays' in weathered granite across southern China, especially in Jiangxi province. The mining methods used for these deposits are either removal of the ore material to leaching tanks or in-situ leaching with ammonium sulphate (Figure 2). These leaching methods use very simple technology but cut out comminution and physical upgrading stages and go straight to dissolution (Figure 2).

The pollution damage from Bayan Obo and associated processing plants in nearby Baotou is significant, and features frequently in newspaper articles (Ali 2014). The extensive land degradation and pollution associated with mining ion adsorption clays is also a serious problem, as is illegal mining, and the Chinese government is taking action to consolidate the REE industry throughout China and improve its environmental performance. Nevertheless, it is a sobering thought that we are all implicated in this environmental damage through everyday pieces of equipment that almost certainly contain Chinese REE.

There are few alternative supplies. Outside of China there are only three substantial active mines. The loparite mine in nepheline syenite at Lovozero, Kola Peninsula, Russia produces REE as a co-product with Nb. Ore treatment is done in Solikamsk, Ural, Russia. Mineral sands at Orissa, India are mined by Indian Rare Earths Ltd. (IRE). This ore is treated on site and the REE separation is also done in India, through a joint venture between IRE and Toyota Tsusho. There is little public information on the environmental performance of either of these operations. The third mine is in weathered carbonatite at Mt Weld, Western Australia, operated by Lynas Corporation Ltd, with ore treatment and REE separation in Kuantan, Malaysia. The mining operation itself has not been controversial but the 'LAMP' separation plant in Malaysia was subject to considerable protest on environmental grounds during its development because of fear of pollution from Th and U in the monazite ore (Ali 2014). The company now publishes details on their website (www.lynascorp.com) of environmental monitoring around the plant and uses international auditable management systems (e.g. ISO14001, OHSAS 18001). They are developing their own chain of assurance with magnet manufacturers. The Mountain Pass (California, USA) carbonatite mine reopened in 2012. It also made an issue of being a more environmentally-friendly source of REE than Chinese producers (Loye 2015) but did not survive the recent low REE prices and closed again in August 2015. So since the crisis of 2010/11, the choice of major supplier has only widened

by one mine (Mt Weld). Processing and separation of REE is becoming progressively more concentrated in China. For example, Solvay, one of few processors outside of China has moved to downstream applications rather than processing REE raw materials. Its two Chinese plants have stopped their REE separation lines and its separation lines at La Rochelle, France are only partly used. The plant at NPM Silmet AS, Sillamae, Estonia only produces separated light REE products.

CONNECTING GEOLOGY AND GEOCHEMISTRY TO RESPONSIBLE SOURCING

Despite the difficulties in current REE supplies, a wide range of REE deposits are being or have recently been explored, providing a particular opportunity to consider how the geology and geochemistry of a deposit can affect responsible mining and sourcing. Deposits include carbonatites, including hydrothermally altered and weathered varieties, alkaline igneous rocks including nepheline syenite and granite, various other hydrothermal deposits, high temperature igneous monazite veins, mineral sands, and various possibilities for REE as by-products; even deep sea muds are being explored (Wall 2014, Chakhmouradian and Wall 2012)

A qualitative comparison of the intrinsic properties of the main varieties of REE ore deposits shows wide variation (Table 1). Five factors have been chosen: (1) the presence of radioactive minerals because this is the main reason for restrictions on shipping and processing of REE ores and concentrates as well as the main public fear, (2) the amount of environmental disturbance likely, considering the size of the likely mine (assumed to be open cast, few REE mines are proposed as underground operations) and amount of rock that needs to be processed to obtain the REE, (3) energy for crushing and grinding, the main energy use in mining, according to whether the deposit is a hard rock requiring considerable energy for comminution or a friable placer or weathered deposit, (4) a measure of resource efficiency based on how easy it is usually to recover a high proportion of the REE from this type of deposit and (5) a measure of whether the REE are a by- of or co-product of another commodity.

Light REE-enriched carbonatites are generally low in Th and U, even if the ore mineral is monazite (see above). As these are some of the highest grade ores, the amount of land disturbed is likely to be low compared to other REE deposits. The energy required for comminution is variable. Carbonatites are not particularly tough rocks but even weathered

deposits require comminution to fine grain size (e.g. 50 μm) if flotation is used to recover the REE minerals.

The nepheline syenite alkaline rock deposits are large and low grade hard rock deposits, thus requiring large amounts of energy for comminution. The mineralogy is complex, and attaining good resource efficiency is difficult, hence the lower mark in this category. There are possibilities for multiple products and an intermediate rating has been given here. The radioactivity of eudialyte as the REE ore mineral in nepheline syenite is low and a particular advantage of these deposits. Other minerals such as steenstrupine may, however, contain higher amounts of Th and U. In alkaline granites, the amount of Th and U can be much higher and such deposits would score red in this category.

Mineral sands, as unconsolidated, easy to process, shallow deposits score well in all categories except radioactivity. With monazite and xenotime derived from granitic rocks, they are at the higher end of the range of Th contents and concentrates are significantly radioactive.

Ion adsorption deposits are easy to mine. They occur close to the surface in weathering profiles typically 15 to 35 m thick. They require disturbance of a large amount of land owing to their low grade (typically about 800 ppm and usually <4000 ppm) but since they are mainly heavy REE deposits, the amounts being dealt with are small and being near the surface, high quality remediation shortly after mining *should* be possible. Little energy is required for mining or processing. The recovery of exchangeable REE cations is likely to be good but insoluble REE minerals will remain in the waste. Th and U values are reported as low although the presence of Th and U-bearing minerals in insoluble residual minerals such as monazite, xenotime, thorite or uraninite is likely to vary according to the protolith composition.

Production of REE as by-products of other ores such as apatite and bauxite is possible (Table 1) and the environmental impact of this depends on whether the production of REE is considered a bonus or, as is more usual, the overall environmental impacts (which may be large, Figure 3) are apportioned to both the major and the by-products.

Overall, the conclusions from this comparison are that mineral sands score well apart from the radioactivity of the ore minerals. Most mineral sand operations ship concentrates from their mine to separate processing factories but their monazite and xenotime concentrates are likely to be too radioactive for transportation, or even for storage. However, this is a challenge that would be overcome if it were possible to install a processing method on site so that Th and U (and Ac) are removed from the ore concentrates, an intermediate product could

be shipped and the Th and U stabilized and returned to source. Ion adsorption clay deposits can also score well as environmentally favourable deposits, so long as good methods are designed to strip mine and remediate rapidly or to carry out safe in-situ leaching. Carbonatites generally appear more environmentally favourable than alkaline rock deposits because of their higher grade. Alkaline rock deposits have the advantage of higher proportions of heavy REE.

QUANTIFYING THE COMPARISON OF DEPOSIT TYPES USING A LIFE CYCLE ASSESSMENT (LCA) APPROACH

It is possible to compare the environmental performance of the production of critical raw materials, using Life Cycle Assessment (LCA), calculating all the energy and material inputs and the associated emissions and waste outputs over an entire life cycle, from raw material acquisition to ultimate disposal (International Organization for Standardization (ISO) 14040 2006a). This method has the advantage of incorporating a wide range of environmental issues into an integrated assessment framework, including climate change, ecotoxicity and resource depletion. Calculations are done with proprietary software that incorporate databases of previous LCAs for inputs such as chemical reagents and power generation. The assessments can stop part way through a life cycle, and most studies of mined materials go 'mine to gate', encompassing mining and some parts of the processing to give an intermediate product used in the next stage of the value chain. To date there have only been a handful of LCAs for REE production, with studies primarily focusing on Bayan Obo (Sprecher et al. 2014; Koltun and Tharumarajah 2014; Zaimes et al. 2015). Sprecher et al. (2014) also extended their LCA to the production of NdFeB magnets. These studies yielded different results (Table 2). For example global warming impacts (GWI) range from 12 to 35.27 kg CO_2 eq at Bayan Obo and acidification has a range from 6.4 to 99.28 kg SO_2 eq. The variation of the REE results can be explained by the fact that different software packages, datasets and methods have been used and different assumptions about the processing routes were made for each LCA. For example, Koltun and Tharumarajah (2014) used a two-step allocation procedure to deal with the co-production of iron ore at Bayan Obo. Comparison of two LCAs done at different times can also be difficult because the inventories in the software are updated periodically as new data become available for specific processes, and to reflect the changing mix of energy generation in the countries in the database.

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An important point that comes from these analyses is the high contribution of chemical reagents, especially when they are manufactured in countries with high fossil fuel use. Although crushing and grinding prior to mineral separation is energy intensive, it has a smaller contribution to greenhouse gas emissions than dissolving the REE minerals and separating the individual REE from each other (Figure 4). Various new processes have been proposed to separate REE but none are in commercial production yet. Learning from nature in order to find novel ways to carry out these processing stages is certainly a challenge to which geochemists could contribute.

Recent work by Vahidi et al. (2016) has examined the environmental performance of ion-adsorption clays. The LCA results indicated that production of REE from ion adsorption clays has a similar GWI as production from Bayan Obo, a lower acidification rate, and a higher cumulative energy demand (CED). It should be noted that the difference in REE composition (i.e. higher HREE content in the ion-adsorption clays) and the use of an economic allocation in the comparison means that the potentially better environmental performance of the ion-adsorption clays is offset by its higher relative economic value. Comparisons could be improved by comparing LCA results for individual REE, e.g. Nd, Dy, Eu rather than grouping the whole set together.

Other challenges specific to use of LCA to evaluate REE production are that there are often limited data available for specific processing steps, and therefore surrogate information is required. This is especially true when comparing deposits that are still in the exploration and development phase. There is also the issue about what factor to measure environmental performance against. Should it be measured against individual REE or against an economic value? Previous studies have tended to incorporate some economic criteria because this is more realistic when considering the high value variation of the individual elements. Ce oxide sells for a few dollars a kg whereas more scarce HREE with specific uses such as Dy and Eu sell for thousands of dollars per kg. Trying to work on the whole set of REE adds a complicating factor but of course this is how the REE occur in ore deposits.

REE production as whole (using figures for Bayan Obo) performs slightly worse than average when compared against LCA results for other metals. For example, Graedel et al. (2015) used an LCA metric for environmental impact, based on the earlier studies of Bayan Obo contained in LCA inventories, and graded the LREE, La, Ce, Pr, Nd low and three of the heavy REE, Eu, Dy, Tb, medium, compared with other metals; all lower than gold, LREE similar to copper and higher than iron.

A limitation of LCA is that although the software packages have been developed to incorporate many factors, such as those discussed in the quantitative comparison above, the results tend to be presented in term of energy use, global warming impact, greenhouse gas emissions, thus missing or apparently downplaying all the other factors of responsible sourcing. LCA also misses the behavioural element of whether a mining company is abiding by the regulations and good practice guidelines. Despite the challenges that exist in LCA, it can be a powerful tool in calculating the environmental performance of REE production, and offers insight into hotspots of production that need further research, as well as calculating values that can feed into full life cycle analyses of manufactured goods. At the moment, the only deposit information available in commercial inventories is for Bayan Obo, and this is a major limitation for consideration of future supplies. Further work should consider formalising a consistent process for LCA use in the context of REE production.

CONCLUSIONS

Most critical raw materials contribute to long manufacturing supply chains for complex devices such as smartphones, computers and cars. It is much more difficult for consumers to engage with the original mining operations in these cases than for products such as jewellery where the raw materials are more obvious. Only high profile humanitarian issues such as conflict minerals have really penetrated these long chains to produce action to help ensure responsible sourcing. There are no responsible mining schemes generally applicable to mid-size critical metal suppliers yet, although there are international management systems and other relevant information that companies can use and make directly available.

Considering the beginning of the supply chain and using the REE as an example, it can be demonstrated that geology and geochemistry have a strong influence on mining and processing techniques, and thus to environmental performance and responsible sourcing. There are plenty of challenges for the geoscience community to find more environmentally-friendly ore types and processing methods, including mitigating the ore dissolution stage, and remediation techniques.

Life cycle assessment and qualitative approaches have different uses in responsible sourcing. LCA is particularly good for technical application in processing design and supply chain analysis. More studies of critical raw materials are needed to show the manufacturers a better choice of raw materials supply routes. LCA is less useful for communication directly to the

public because of the way it condenses information. A single issue, such as radioactivity or landscape degradation, can outweigh all other factors in pubic consideration and will have to be addressed as highest priority. These issues of responsible sourcing are the same for critical and non-critical raw materials.

For REE, it is important to consider that most users still purchase from China and much of the REE supply chain sits in China. Several mining projects under development outside China have agreements to sell to Chinese processors. A particular challenge for Chinese REE producers is that they have to demonstrate both an improvement in their environmental and social performance and show that there is enough diversity in the World market to guarantee a secure supply.

Acknowledgements

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Box

Solvent extraction of REE

Perhaps the most complex chemical challenge of REE production is that applications need individual high purity REE. The separation of the natural mixtures into individual pure REE is particularly difficult, chemically intensive and has always been a challenge in terms of science and technology and also economics (Lucas et al. 2015). A breakthrough in producing a separation process that uses more environmentally-friendly chemicals and/or can be applied at the same time as the first processing, or during in-situ leaching would be a major advance in responsible sourcing of REE. Historically REE separation was done by selective

crystallization and then later by ion exchange and now by solvent extraction. A number of new techniques have been proposed but none are yet being used commercially.

Solvent Extraction is currently the only industrial scale REE separation process. The separation is done step by step, with a mixer-settler technology and each step performed in equipment called a Solvent Extraction battery. Each solvent extraction battery can separate one group of REE into two sub-groups, or a mixture of two REE into two pure individual REE. So, the separation of mixture of n REEs into n individual REE will need n-1 solvent exchange batteries. Industrially, REE separation processes are all done in a battery of mixer-settlers with counter-current flows: the purification of each REE can reach as high as 6N (99.9999%).

The choice of solvent depends on: selectivity (for the REE^{3+} valency), loading capacity and how the extracting molecule affects the energy and chemical reagent consumption. The classical extractants used are Ethyl2hexyl Ethyl2hexyl phosphonic acid (H(EH)EHP), Tributyl phosphate (TBP) and Aliquat 336. H(EH)EHP gives the highest total difference of partition coefficients between REE: $P(Lu^{2+})/P(La^{3+}) > 10^6$ (Figure 1 Box). It is the most selective extractant along the lanthanoid series and can be used for all REE separations. Nevertheless, tri butyl phosphate in a nitrate medium can be used for La/Ce/Pr/Nd separation and Aliquat 336 in a nitrate medium can be used for some light and heavy REE separations (Figure 1 Box). The loading capacity of a solvent, defined as the maximum quantity of REE that this solvent can load can be improved by lower molecular weight and lower viscosity of the solvent.

The chemical and energy consumptions depend on the extraction mechanisms. All the solvents can be classified into three different types of extracting molecules: solvating agents or neutral extractants (e.g tributyl-phosphate, TBP) which consume steam and water, anion exchangers (e.g. Salts of trilauryl methyl ammonium and of tricapryl methyl ammonium) which also consume steam and water and cation exchangers (e.g. Ethyl2hexyl,ethyl2hexyl phosphonic acid, HEHEHP) which consume basic chemicals (NaOH or NH_4OH) in the extraction section and acids (HCl or HNO_3) in the stripping section.

The usual way to classify solvent extraction processes is to distinguish between the chloride process and the nitrate process. The chloride process is the most widely used, in all Chinese plants. Its advantages are that the same solvent can be used for all the REE separations because H(EH)EHP is selective throughout the lanthanoid series (Figure 1 Box) and the liquid wastes contain NaCl which can usually be released into the environment with no

constraints. The main disadvantage is the large consumption of HCl and NaOH. The nitrate process has lower operating costs than the chloride process. Solvating and basic extracting molecules can both be used and the solvents based on these molecules consume almost no chemicals. Ce and Eu are easy to convert to the 4+ and 2+ oxidation states, respectively, and this can be used to facilitate their separation.

Figure captions

Figure 1 Summary of mining and processing routes for REE deposits. Ores are divided into three types: hard conventional such as igneous carbonatite and alkaline igneous rocks, soft conventional such as mineral sands and easily leachable which includes ion adsorption clays.
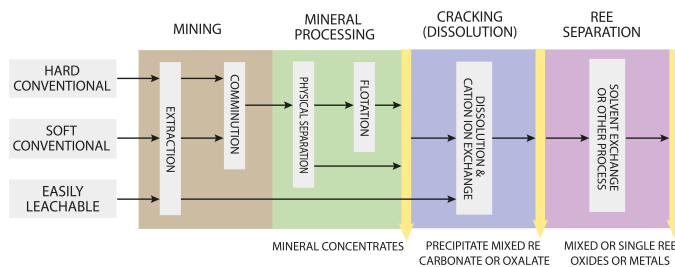

Figure 2 In situ leaching pond for ion adsorption clay REE deposit, China. A low technology technique, in which drainage holes at the rear of the collection pond bring the leach solution down the hillside through the weathered granite. In theory, this could be a low environmental impact method to produce REE but it depends on the chemicals used and how well they are controlled. Photo courtesy of Alain Rollat.

Figure 3 Waste tips associated with the apatite mines in the Khibiny nepheline syenite complex, Kola peninsula, Russia.

Figure 4 Greenhouse gas emissions equivalent per kg of REO produced calculated from a life cycle assessment of mining, concentrating Bayan Obo REE ore, dissolving (cracking) the two ore minerals, bastnäsite and monazite to release their REE, and then separating the REE from each other (Koltun and Tharumarajah 2014).
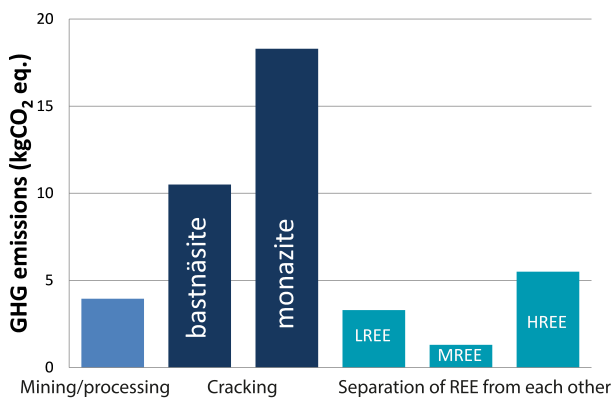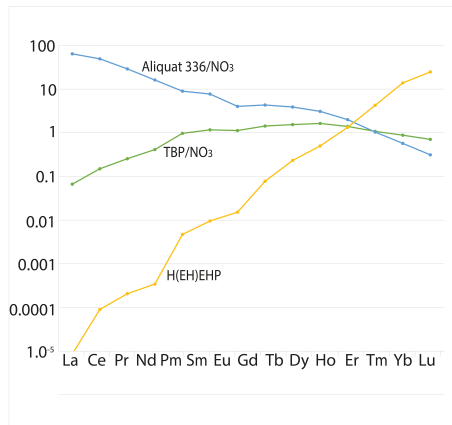

Figure 1 Box. Relative partition coefficients of RE^{3+}, i.e. $[P(RE^{3+})]$ for the three extractants, Ethyl2hexyl Ethyl2hexyl phosphonic acid (H(EH)EHP), Tributyl phosphate in a nitrate medium (TBP/NO_3) and Aliquat 336 in a nitrate medium ($Aliquat^{336}/NO_3$). The scale is normalized to a partition of one for Y. The larger the difference of $P(RE^{3+})$ between two adjacent REE, the more selective the extractant. Modified from Lucas et al. (2015).

Aliquat 336/NO₃

TBP/NO₃

H(EH)EHP

100
10
1
0.1
0.01
0.001
0.0001
1.0⁻⁵

La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Tables

Table 1 Examples of REE deposits and qualitative analysis of their mining and processing characteristics

Ore type	Energy for crushing and grinding	Grain size /Difficulty of beneficiation	Chemicals (acid, flotation reagent)	Radioactivity: ore mineral and host rock	Amount of rock to be moved*	By-products
Carbonatite	Med High	Variable – 10 µm	Flotation	Low-med.	Low	Not usually
Weathered carbonatite	Medium	10 µm and finer	Flotation	Low – med.	Low	Not usually
Alkaline rock	High	µm and larger	High	Variable	High	Coproducts
Ion adsorp-tion clay (in-situ leaching)	None	n/a	Leaching	Low	Low	None
Mineral sand (placer)	None –low	10 - 100 µm	Low	High	High	REE by-product of TiO_2 etc.
By-product of apatite	High	100 µm-mm	Medium	Low	High	Fertiliser manufacture
Red mud	bauxite	n/a,REE from red mud	Medium?	Low	High	Al production

*i.e. low grade = large amount of rock

Table 2. Summary of four LCAs with a functional unit of 1 kg of REO, three from Bayan Obo (China), highlighting different results obtained from the same deposit, plus one for a Chinese ion adsorption deposit.

Factor	unit	Bayan Obo 1	Bayan Obo 2	Bayan Obo 3	Ion adsorp-tion clay
Global warming	kg CO_2 eq	12-16	32.29-32.49	22.98-35.27	20.9-35.5
Acidification	kg SO_2 eq	6.4-8.8	N/A	96.27-99.28	0.165-0.288
Eutrophication	kg N eq	0.04-0.06	N/A	0.18-0.27	0.303-2.87
Respiratory effects	kg PM2.5 eq	N/A	N/A	0.16-0.18	0.026-0.045
Ozone depletion	kg CGC-11 eq E-06	2-3.5	N/A	3.8-20	2.4-3.2
Cumulative energy demand	MJ	174-232	169.2-179.5	315-578.8	255-388

Data from Sprecher et al. (2014), Koltun and Tharumarajah (2014), Zaimes et al. (2015), Vahidi et al. (2016)
All results are presented as a range from low to high
N/A= no result available for this factor