Most critical raw materials, such as the rare-earth elements (REEs), are starting products in long manufacturing supply chains. Unlike most consumers, geoscientists can become involved in responsible sourcing, including best environmental and social practices, 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 the emissions and waste from mining and processing can be quantified, and studies for REEs show little difference between ‘hard rocks’, such as carbonatites, and easily leachable ion-adsorption clays. The reason is the similarity in the embodied energy in the chemicals used for leaching, dissolution and separation.

**INTRODUCTION**

Current technologies use a wider range of elements in their fabrication 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 used in electronics need tantalum; permanent magnets of all types, ranging from the tiny speakers in smartphones to huge tonne-weight magnets in large wind turbines, are made of NdFeB. Lithium ion batteries, which also contain cobalt and graphite, are now widespread and are rapidly increasing in use. The total amounts needed of many of the aforementioned elements, despite their many uses, 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 mines at any one time is limited. For commodities such as indium, there are no mines: smelter by-products are the only source. Recycling rates are often low. The potential supply risk is high, and such elements are called ‘critical’. The concept of ‘criticality’ is 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).

Because 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). Responsible mining takes into account 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, as final consumers, can be assured 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 (REEs), 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 who are members of the International Council on Mining and Metals (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’ (columbite–tantalite; the main ore of Ta) are covered under legally binding social regulations. Some manufacturers, such as Fairphone (a manufacturer of smartphones free of conflict minerals) have attempted to understand their supply chain and to connect consumers with the raw materials used. For most complex products, though, it is hard for the consumer to make a connection to the mines that have produced the raw materials. The main drivers for responsible mining of most critical metals are not 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
SOLVENT EXTRACTION OF RARE-EARTH ELEMENTS

Perhaps the most complex chemical challenge for producing REEs is that applications need individual high REE purity. The separation of the natural mixtures into an individually pure REE is particularly difficult, chemically intensive and has always been a challenge in terms of science, technology and economics (Lucas et al. 2015). A breakthrough in developing a separation process that could use more environmentally friendly chemicals and/or be applied at the same time as first-stage processing, or during in-situ leaching, would be a major advance in responsible sourcing of REEs. Historically, REE separation was done first by selective crystallization, then ion exchange methods, and now it is mostly done by solvent extraction. A number of new techniques have been proposed but none are 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 REEs into two sub-groups, or a mixture of two REEs into two pure individual REEs. So, the separation of mixture of n REEs into n individual REEs 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 (i.e. 99.9999% pure).

The choice of solvent depends on the following: selectivity (for the REE valency), loading capacity, and how the extracting molecule affects the energy and chemical reagent consumption. The classical extractants used are 2-Ethylhexyl phosphonic acid, mono-2-ethylhexyl ester (H(EH)EHP), tributyl phosphate (TBP) and Aliquat 336 (N-Methyl-N,N,N-trioctylammonium chloride). It is the extractant H(EH)EHP that gives the highest total difference of partition coefficients between REEs: $P(\text{Lu}^{3+})/P(\text{La}^{3+}) > 10^6$ (Fig. 1 Box). It is the most selective extractant along the lanthanoid series and can be used for all REE separations. Nevertheless, tributyl 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 (Fig. 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. TBP), which consume steam and water; anion exchangers (e.g. Salts of triauryl methyl ammonium and of tricapryl methyl ammonium), which also consume steam and water; and cation exchangers (e.g. H(EH)EHP), which consume basic chemicals (NaOH or NH₄OH) in the extraction section and acids (HCl or HNO₃) 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, and is used in all Chinese plants. The advantages of the chloride process are that the same solvent can be used for all the REE separations because H(EH)EHP is selective throughout the lanthanoid series (Fig. 1 Box) and because 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. Cerium and europium are easy to convert to their 4+ and 2+ oxidation states, respectively, and this can be used to facilitate their separation.

RARE-EARTH SUPPLY

An introduction to the REEs has been given by Chakhmoukhian and Wall (2012) in a previous issue of Elements. Other reviews of REEs as critical metals are given in Wall (2014) and Verplanck and Hitzman (2016). As mentioned above, the REEs (the term is used here to include 15 elements: Y, plus La through to Lu, but 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 REEs 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 REEs 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 REEs from the heavy REEs (Chakhmouhrdian and Wall 2012) all members of the series occur together.

The production of REEs usually follows conventional mining techniques. Production starts with open pit mines; this is followed by comminution (crushing and grinding) of the ore; then comes 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 (Fig. 1). The REE minerals then need to be dissolved (‘cracked’) to release the REEs. An intermediate mixed REE carbonate or oxalate produced at this stage can now be shipped. The next step, required in all cases, is further processing to separate the REEs from each other, which is the most important step in adding value and leads to the high purity REE metals and oxides that are sold to the manufacturing industry (Fig. 1).

By far the largest REE mine is in altered and metamorphosed carbonate at Bayan Obo, Inner Mongolia (China), with smaller carbonate/alkaline rock and carbonatite mines at Weishan County in Shandong Province (China).
and the Maoniuping/Dalucao area in Sichuan Province (China), both important sources for the ‘light’ REEs (La–Sm) (LREEs). All are open cast quarries. The higher atomic number ‘heavy’ REEs (Eu–Lu) (HREEs) 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 HREE deposits are either removal of the ore material to leaching tanks or in situ leaching with ammonium sulphate (Fig. 2). These leaching methods use very simple technology but cut out the comminution and physical upgrading stages and go straight to dissolution (Fig. 2).

The pollution damage from Bayan Obo and associated processing plants in nearby Baotou is significant, frequently featured in newspaper articles (Ali 2014). The extensive land degradation and pollution associated with mining the ion-adsorption clays is also a serious problem, as is illegal mining. 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 REEs.

There are, however, 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 REEs as a co-product with Nb. Ore treatment is done in Solikamsk (Russia). Mineral sands at Orissa (India) are mined by Indian Rare Earths Ltd. This ore is treated on site and the REE separation is also done in India, through a joint venture between Indian Rare Earths Ltd. 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 Mount 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 Lynas Advanced Materials Plant (‘LAMP’) in Malaysia, which was needed to separate the REEs, 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. ISO 14001, OHSAS 18001). The company is also developing their own chain of assurance with magnet manufacturers. The Mountain Pass (California, USA) carbonatite mine re-opened in 2012. It also made an issue of being a more environmentally friendly source of REEs than the 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 (Mount Weld). Processing and separation of REEs is becoming progressively more concentrated in China. For example, Solvay, a chemical company based in Belgium and one of the 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 in Sillamae (Estonia) only produces separated LREE products.

**CONNECTION 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 (both hydrothermally altered and weathered varieties), alkaline igneous rock (including nepheline syenite and granite), other types of hydrothermal deposits, high-temperature igneous monazite veins, mineral sands, and REEs as by-products of other ores. Even deep-sea muds are being explored (Chakhmouradian and Wall 2012; Wall 2014).

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 to characterise the different types of REE deposits: (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 the amount of rock that needs to be processed to obtain the REE; (3) the energy needed for crushing and grinding, which is the main energy use in mining, according to whether the deposit is a hard rock that requires considerable energy for comminution or is a friable placer or weathered deposit; (4) the resource efficiency, based on how easy it usually is to recover a high proportion of the REEs from the type of deposit in question; (5) the measure of whether the REEs are a by- or a 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, for example, are not particularly tough rocks, but even weathered deposits require comminution to a fine grain size (~50 μm) if flotation is used to recover the REE minerals.

The nepheline syenite alkaline rock deposits are large, low grade, hard rock deposits, requiring large amounts of energy for comminution. The mineralogy is complex, and attaining good separation and thus resource efficiency is difficult. There are possibilities for multiple products, and an intermediate rating has been given for this situation (Table 1). The radioactivity of eudialyte as the REE ore mineral in nepheline syenite is low and is 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, hence the ‘variable’ label in Table 1.

Mineral sands, being unconsolidated, easy to process, and 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, making derived concentrates significantly radioactive.

Ion-adsorption deposits (i.e. REEs adsorbed onto clays, which are usually the products of granite weathering) are the ones that tend to hold the HREEs and are easy to mine. They occur close to the surface in weathering profiles and are typically 15–35 m thick. They require disturbance of a large amount of land, owing to their low grade (typically about 800 ppm, but usually <4,000 ppm). On the plus side, the amounts of HREEs are small and near the surface, making high-quality remediation shortly after mining possible. Also, 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. Values of Th and U are 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 REEs as by-products of ores such as apatite and bauxite is possible (Table 1) and the environmental impact of this depends on whether the production of the REEs is considered a bonus or whether, as is more usual, the overall environmental impacts (which may be large, see Fig. 3) are apportioned to both the major products 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 could be overcome if a processing method was installed on site so that Th and U (and Ac) were removed from the ore concentrates. Then, 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. Carbonatitites generally appear more environmentally favourable than alkaline rock deposits because of their higher grade. Alkaline rock deposits have the advantage of higher proportions of HREEs.

### Table 1. Examples of Rare-Earth Element (REE) Deposits and Qualitative Analysis of Their Mining and Processing Characteristics.

<table>
<thead>
<tr>
<th>Ore type</th>
<th>Energy for crushing and grinding</th>
<th>Grain size/ Difficulty of beneficiation</th>
<th>Chemicals (acid, flotation reagent)</th>
<th>Radioactivity: ore mineral and host rock</th>
<th>Amount of rock to be moved</th>
<th>By-products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonatite</td>
<td>Medium – High</td>
<td>Variable – 10 μm</td>
<td>Flotation – medium</td>
<td>Medium</td>
<td>Low</td>
<td>Not usually</td>
</tr>
<tr>
<td>Weathered carbonatite</td>
<td>Medium</td>
<td>10 μm and finer</td>
<td>Flotation – medium</td>
<td>Low–Medium</td>
<td>Low</td>
<td>Not usually</td>
</tr>
<tr>
<td>Alkaline rock</td>
<td>High</td>
<td>Variable 1 μm and larger</td>
<td>Variable</td>
<td>Variable</td>
<td>High</td>
<td>Co-products common</td>
</tr>
<tr>
<td>Ion adsorption clay</td>
<td>None</td>
<td>Beneficiation not needed</td>
<td>Leaching, so can be high</td>
<td>Low</td>
<td>Low</td>
<td>None</td>
</tr>
<tr>
<td>(in-situ leaching)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral sand (placer)</td>
<td>None–Low</td>
<td>10 – 100 μm</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>from TiO₂, zircon etc</td>
</tr>
<tr>
<td>By-product of igneous apatite</td>
<td>High</td>
<td>100 μm–mm</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>from fertiliser manufacture</td>
</tr>
<tr>
<td>Red mud</td>
<td></td>
<td>n/a REE from red mud</td>
<td>Medium?</td>
<td>Low</td>
<td>High</td>
<td>from Al production</td>
</tr>
</tbody>
</table>

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

---

**Figure 3** Waste tips associated with the apatite mines in the Khibiny nepheline syenite complex, Kola Peninsula (Russia).
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 by using the “life cycle assessment” (LCA) approach. An LCA is performed by 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, primarily focusing on Bayan Obo (Sprecher et al. 2014; Koltun and Tharumarajah 2014; Zaimes et al. 2015). Sprecher et al. (2014) extended their LCA to the production of NdFeB magnets. These studies yielded different results (Table 2). For example, global warming impacts range from 12 to 35.27 kg CO$_2$ equivalent (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 that 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 because of the need to reflect the changing mix of energy generation in the countries in the database.

An important point that comes from these analyses is the high contribution made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by 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 made by chemical reagents, especially when they are manufactured in countries with high fossil fuel use.

Recent work by Vahidi et al. (2016) has examined the environmental performance of ion-adsorption clays. The LCA results indicated that production of REEs from ion-adsorption clays has a similar global warming impact as production from Bayan Obo, a lower acidification rate than from Bayan Obo, and a higher cumulative energy demand. 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 REEs, e.g. Nd, Dy, or Eu, rather than grouping the whole set together.

Other challenges specific to using LCAs in evaluating REE production are that there are often limited data available for specific processing steps. 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 an 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. Cerium

<table>
<thead>
<tr>
<th>Table 2</th>
<th>SUMMARY OF FOUR LIFE-CYCLE ASSESSMENTS (LCAs) with a functional unit of 1 kg of rare-earth oxides (REOs), three from Bayan Obo (Inner Mongolia, China), highlighting different results obtained from the same deposit, plus one for a Chinese ion-adsorption deposit.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>Unit</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO$_2$ eq</td>
</tr>
<tr>
<td>Acidification</td>
<td>kg SO$_2$ eq</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM2.5 eq</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq x 10$^{-6}$</td>
</tr>
<tr>
<td>Cumulative energy demand</td>
<td>MJ</td>
</tr>
</tbody>
</table>

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

The eq units simplify all of the chemicals causing each factor into one equivalent unit, e.g. kg CO$_2$ eq includes other gases responsible for global warming such as methane. PM2.5 = atmospheric particulates smaller than 2.5 µm diameter. CFC-11 = ozone-depleting chemicals equivalent to trichlorofluoromethane.

N/A = no result available for this factor

FIGURE 4 Greenhouse gas (GHG) emissions equivalent per kg of rare-earth oxide produced calculated from a life cycle assessment of a) mining, concentrating Bayan Obo REE ore; b) dissolving (cracking) the two ore minerals bastnaite and monazite to release their REEs; c) separating the light (L), medium (M) and heavy (H) REEs from each other. After Koltun and Tharumarajah (2014).
oxide sells for a few dollars a kg whereas the scarcer HREEs that have specific uses, such as Dy and Eu, sell for thousands of dollars per kg. Trying to work on the whole set of REEs adds a complicating factor but, of course, this is how the REEs occur in ore deposits.

Production of REEs as whole (using data for Bayan Obo) performs slightly worse than 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. Graedel et al. (2015) graded the LREEs (La, Ce, Pr, and Nd) as having low environmental impact, and three of the HREEs (Eu, Dy, Tb) as medium, when compared with other metals. All the REEs had a lower environmental impact (in terms of production) than gold, whereas the LREEs themselves were similar to copper and higher than iron.

A limitation of the LCA approach 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, and greenhouse gas emissions. Thus, the results either miss or apparently downplay all the other factors of responsible sourcing. The LCA approach also misses the behavioural element of whether a mining company is abiding by the regulations and following good practice guidelines. Despite the doubters that exist in LCAs, it can be a powerful tool in calculating the environmental performance of REE production and of offering 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 (China), and this is a major limitation when considering future supplies. Further work will be needed to formalise a consistent process for LCA use in the context of REE production.

CONCLUSIONS
Most critical raw materials contribute to the long supply chains used for the manufacture of 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 mining operations for gemstone products used in jewellery where the raw materials are more obvious. Only high-profile humanitarian issues, such as conflict minerals, have really penetrated these long supply chains to produce the action needed to help ensure responsible sourcing. As yet, there are no responsible mining schemes generally applicable to mid-size critical metal suppliers, 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 REEs as an example, it can be demonstrated that geology and geochemistry have a strong influence on mining and processing techniques. This, in turn, feeds into environmental performance and responsible sourcing. There are plenty of challenges for the geoscience community to find more environmentally friendly ore types, processing methods (including mitigating the ore dissolution stage), and remediation techniques.

Life cycle assessment and qualitative approaches have different uses in responsible sourcing. An LCA is particularly good for refining a 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. However, an LCA is less useful for communicating directly to the public because of the way it condenses information. A single issue, such as radioactive or landscape degradation, can outweigh all other factors in public consideration and will have to be addressed as highest priority. These issues of responsible sourcing are the same for critical as for non-critical raw materials.

For REEs, 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.

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