A Detailed Assessment of Global Rare Earth Element Resources: Opportunities and Challenges*

Zhehan Weng,[1,†] Simon M. Jowitt,[2] Gavin M. Mudd,[1] and Nawshad Haque[3]

[1] *Environmental Engineering, Department of Civil Engineering, Monash University, Wellington Road, Clayton, VIC 3800, Australia*

[2] *School of Earth, Atmosphere and Environment, Monash University, Wellington Road, Clayton, VIC 3800, Australia*

[3] *CSIRO Mineral Resources, Private Bag 10, Clayton South, VIC 3169, Australia*

Abstract

Rare earth elements (REE) are indispensable to infrastructure, technology, and modern lifestyles, which has led to an increasing demand for these elements. The current global rare earth oxides (REO) market is dominated by Chinese production, which peaked in 2006 at 133,000 tonnes REO per year, accounting for some 97.1% of global production, causing concern about the long-term supply of REE resources. Although the REE consist of 17 individual elements (15 lanthanides plus scandium and yttrium) that are hosted by numerous types of mineralization, the relatively modest scale of the global REE mining sector has limited our knowledge of REE mineral resources and mineralizing systems compared to metals such as copper and iron, which are produced in much larger quantities.

In order to quantitatively analyze the mineralogy, concentrations, and geologic types of REE deposits, we compiled a global dataset of REE mineral resources based on the most recently available data (2013–2014). This compilation yields minimum global contained total rare earth oxides plus yttrium oxide (TREO + Y) resources of 619.5 Mt split between 267 deposits. Deposits with available grade and tonnage data (260 of the 267 deposits in our database) contain some 88,483 Mt of mineral resources at an average concentration of 0.63% TREO + Y, hosting 553.7 Mt TREO + Y. Of the 267 total deposits in our database, some 160 have mineral resources reported using statutory mining codes (e.g., JORC, NI43-101, SAMREC), with the remaining 107 projects having CRIRSCO-noncompliant mineral resources that are based on information available in the industry literature and peer-reviewed scientific articles.

Approximately 51.4% of global REO resources are hosted by carbonatite deposits, and bastnäsite, monazite, and xenotime are the three most significant REE minerals, accounting for >90% of the total resources within our database. In terms of REE resources by individual country, China dominates currently known TREO + Y resources (268.1 Mt), accounting for 43% of the global REO resources within our database, with Australia, Russia, Canada, and Brazil having 64.5, 62.3, 48.3, and 47.1 Mt of contained TREO + Y resources, respectively. Some 84.3 Mt TREO + Y is hosted within tailings (dominated by tailings from Bayan Obo but with smaller resources at Palabora, Steenkampskraal, and Mary Kathleen) and 12.4 Mt TREO + Y is hosted by monazite within heavy mineral sands projects, illustrating the potential for REO production from resources other than traditional hard-rock mining.

Global REE resources are dominated by the light REE, having an average light REO (LREO; La-Gd) to heavy REO (Tb-Lu and Y) ratio of 13:1. These REE deposits contain an average of 81 ppm Th and 127 ppm U, indicating that radioactive waste associated with REE extraction and refining could be a concern. Modeling the 2012 global production figures of 110 kt TREO + Y combined with an assumed 5% annual growth in REE demand indicates that known REE resources could sustain production until 2100 and that geologic scarcity is not an immediate problem. This suggests that other issues such as environmental, economic, and social factors will strongly influence the development of REE resources.

Introduction

Rare earth elements (REE) have crucial industrial uses and are indispensable to the development of modern defense systems, green technologies, and electronic applications. This is exemplified by REE alloys and permanent magnets, both of which are considered essential for renewable energy technology (e.g., electric vehicles, energy-efficient lighting, and wind power turbines). From a production perspective, the REE are primarily reported as rare earth oxides (REO; U.S. Environmental Protection Agency [USEPA], 2012), and the growth of REE-dependent technologies and applications is expected to significantly increase global demand for the REO over coming decades (U.S. Department of Energy [USDOE], 2010; Hoenderdaal et al., 2013; Humphries, 2013).

The global REO market peaked in 2006 with 133,000 tonnes (t) of produced REO and is dominated by Chinese production, which accounted for 97.1% of global production in 2006 (United States Geological Survey [USGS], 1997–2015). Historical global REO production is shown in Figure 1. For various political, economic, and environmental reasons, the Chinese government from about 2006 implemented mandatory export restrictions on REE, tungsten (W), and molybdenum (Mo) (State Council Information Office of the People's Republic of China [SCIO], 2012). From 2006 to 2011, the REO export quota for Sino-foreign joint ventures in China decreased from 16,070 to 7,746 t, whereas domestic REE producers and traders had export quotas reduced from 45,000 to 22,512 t (Morrison and Tang, 2012). These restrictions led to a decrease in the
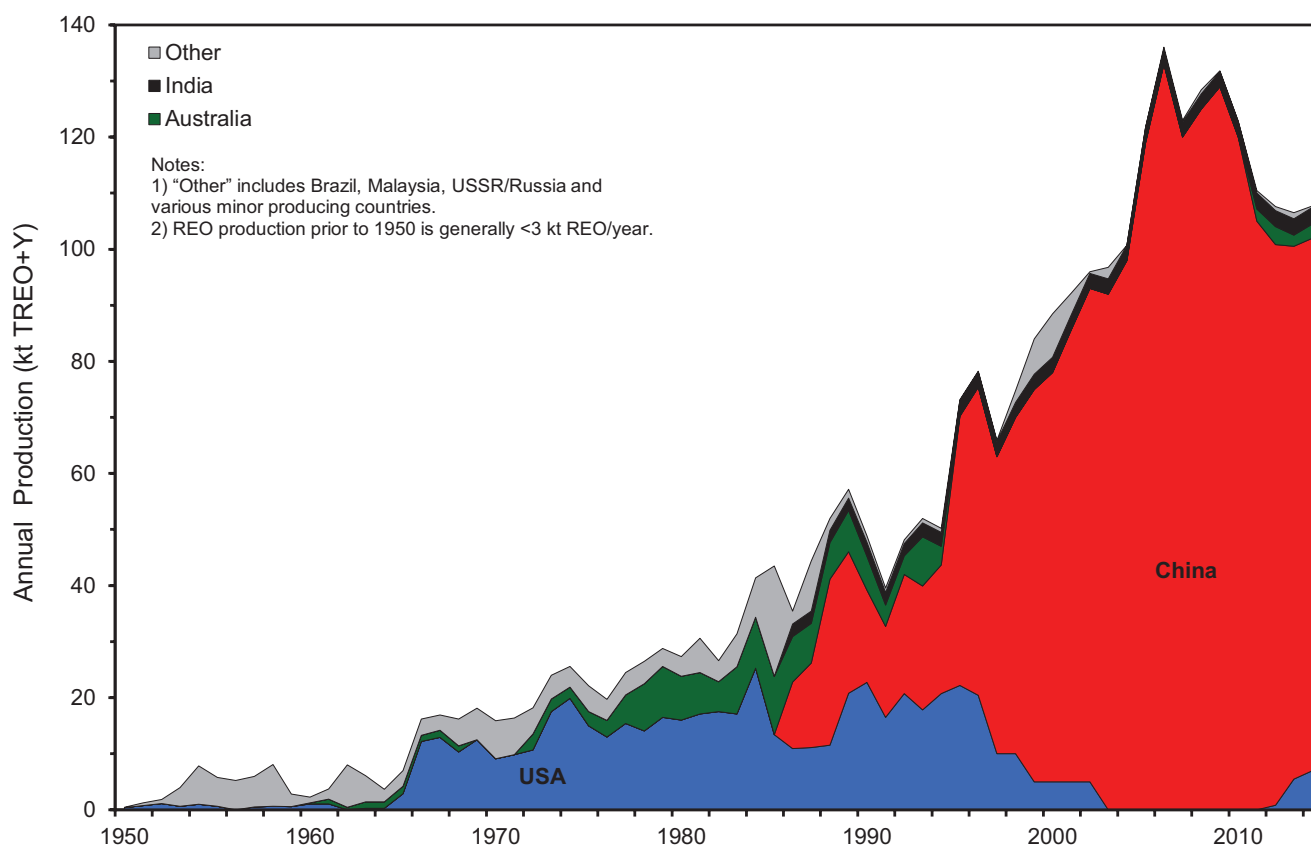
FIG. 1. Historical TREO + Y production split by country. Average global REO production data are from the U.S. Bureau of Mines (USBoM, 1927–1934, 1933–1996) and the U.S. Geological Survey (USGS, 1901–1927, 1994–2011, 1997–2015). Australian REO are based on monazite production data, assuming a minimum of 60% contained TREO + Y (BoMRGG, 1960–1985).

Chinese REO export quota from 61,560 t in 2006 to 30,246 t in 2011. In addition, China's annual REO production also gradually declined from 133,000 t in 2006 to 95,000 t in 2013 (USGS, 1997–2015). These restrictions on REO exports were coincident with an internal drive in China to encourage domestic REO consumption, including high-end and high-tech REE-related processing and manufacturing. The Chinese restrictions on REO exports caused a significant increase in global REO prices (Humphries, 2013), although these prices have declined recently (USGS, 1997–2015). These quotas also highlighted concerns about the future supply of critical metals, driven not only by economics but also by geopolitical considerations, industrial and economic interests, supply monopoly, and prioritization of domestic downstream industries (Hayes-Labruto et al., 2013; Moss et al., 2013a, b; Wübbeke, 2013). This was noted by the World Trade Organization (WTO), which in 2014 announced the settlement of China's REE export dispute and the removal of the Chinese REE export quota (WTO, 2014).

Nevertheless, China's REE export restrictions exemplify the risk inherent in having the global supply of the REO dependent on a dominant supplier or country, which obviously poses significant risks to the security of supply of these important elements. This situation has led to a widespread interest in quantifying the availability of these important elements (e.g., USDOE, 2010; Moss et al., 2011; Naden, 2014). Thus, there is need for a comprehensive assessment of global REE mineral resources to identify key opportunities, uncertainties,

and challenges for the global REE industry. The critical aspects needed for such an assessment include identifying major REE mineral deposit types, classifying these deposits by REE mineralogy, and identifying the presence or absence of potential by-/co-products (e.g., Fe, Ti, Nb, and Zr) and/or hazardous impurities (e.g., U and Th). These data will provide a rigorous foundation for industries and governments to initiate the development of sustainable, secure, and economic global REE supplies.

The International Union of Applied and Pure Chemistry (IUPAC) defines the REE as the 15 lanthanide elements plus Sc and Y, as shown in Table 1 (IUPAC, 2005). Each of the REE has distinctive characteristics and usages, with the lanthanide elements divided by electron shell configuration into the light REE (LREE; La to Gd) and the heavy REE (HREE; Tb to Lu), although the mining industry does not currently use such a definitive classification of the split between LREE and HREE, with some projects (e.g., Buckton, Browns Range, etc.) defining the LREE as including La, Ce, Pr, and Nd, whereas the HREE (as reported by the mining companies involved) include Sm, Eu, and Gd (e.g., Eccles et al., 2013). Furthermore, the term medium REE (MREE; Sm to Gd) is also used in some industrial reporting (e.g., Ashram, Charley Creek), but does not have a formal IUPAC classification. Y and Sc are not formally classified as either LREE or HREE but have a chemical affinity with the lanthanide group of elements, with these chemical affinities meaning that Y is also

TABLE 1. Summary of the Chemistry and Average Crustal Abundances of the REE[1]

Element abbreviation	Atomic number	Element name	IUPAC classification[2]	Average crust (ppm)[3]	Usages
La	57	Lanthanum	Light	31	Optics, batteries, catalysis, hydrogen storage
Ce	58	Cerium	Light	63	Chemical applications, coloring, polishing glass, catalysis, hybrid vehicles
Pr	59	Praseodymium	Light	7.1	Magnets, lighting, optics
Nd	60	Neodymium	Light	27	(SmCo) magnets, lighting, lasers, optics, hybrid vehicle batteries
Pm	61	Promethium	Light	–	Limited use due to radioactivity, used in luminous paint and atomic batteries; very rare in nature (due to its short half-life)
Sm	62	Samarium	Light	4.7	Magnets, lasers, masers, lightweight magnets
Eu	63	Europium	Light	1	Lasers, lighting, medical applications
Gd	64	Gadolinium	Light	4	Magnets, glassware, lasers, X-ray contrast agent, computer applications, medical applications
Tb	65	Terbium	Heavy	0.7	Lasers, lighting, lightweight magnets
Dy	66	Dysprosium	Heavy	3.9	Magnets, lasers, hybrid vehicle batteries
Ho	67	Holmium	Heavy	0.83	Lasers
Er	68	Erbium	Heavy	2.3	Lasers, medical applications, neutron-absorbing control rods in nuclear industry
Tm	69	Thulium	Heavy	0.3	X-ray generation
Yb	70	Ytterbium	Heavy	2	Lasers, chemical industry applications
Lu	71	Lutetium	Heavy	0.31	Medical applications, chemical industry applications
Sc	21	Scandium	N/A	14	Alloys in aerospace engineering, lighting, fuel cells
Y	39	Yttrium	Heavy	21	Lasers, superconductors, microwave filters, lighting, ceramic

– = concentration too low to assess as a result of the short radioactive half-life of this element
[1] Adapted from Weng et al. (2013)
[2] The chemical classification of the REE uses the configuration of electrons in the outer shell of the element, with the LREE having no paired clockwise- and counterclockwise-spinning electrons, whereas the HREE have both clockwise- and counterclockwise-spinning electrons; Sc and Y are chemically similar to these elements and are also included, with Y classified as a heavy rare earth element, although the properties of Sc are not similar enough to either LREE or HREE to allow further chemical classification
[3] From Rudnick and Gao (2003)

often considered an HREE. The short half-life of Pm means that it is rarely extracted during the exploitation of REE mineral deposits but, rather, may be produced as by-product from the nuclear industry, and as such is excluded from our dataset. Here, we split the REE according to the IUPAC classification into the LREE (La, Ce, Pr, Nd, Sm, Eu, and Gd) and the HREE (Tb, Dy, Ho, Er, Tm, Yb, and Lu).

In contrast to their name, some of the REE are relatively abundant in the Earth's crust and, although typical REE abundances in the Earth's upper crust vary significantly, Ce and La have average crustal concentrations of 63 and 31 parts per million (ppm), respectively—both higher than the average crustal concentrations of Cu (28 ppm) and Pb (17 ppm; Rudnick and Gao, 2003). In comparison, Tm and Lu have average crustal concentrations of 0.3 and 0.31 ppm, respectively, much lower than the majority of other economically important metals, but still higher than Au, Ag, and the platinum group elements (Rudnick and Gao, 2003).

The REE are rarely (if ever) present as native metals in the natural environment; instead, they often substitute for other elements within the matrix of certain minerals, especially phosphates and carbonates. At present, the most important economic REE-bearing minerals are bastnäsite ((Ce,La)(CO$_3$)F), monazite ((Ce,La,Nd,Th)PO$_4$), and xenotime (YPO$_4$; Jordens et al., 2013), although the REE can substitute into the matrix of more than 200 individual minerals (Jones et al., 1996). The substitution-dominated nature of REE minerals and the low difference in density between these minerals and their associated gangue means that REE ores are complicated

to process, especially when compared to more commonly processed sulfide and oxide ores (e.g., Cu, Pb, and Zn). In addition, the chemical similarities between the REE mean that the separation and purification of individual REE, a necessary step in the vast majority of end uses, is also difficult, with both concentration and refining being chemically and energy intensive (USEPA, 2012). Furthermore, the geologic and mineralogical variability of REE deposits means that the extraction, concentration, and processing of REE ores is highly variable from project to project, and is often deposit type or even individual deposit specific. The geochemical behavior of the REE also means that REE-bearing minerals often contain uranium and thorium, as is evidenced by the high concentrations of Th that are often present in REE-bearing monazite (Long et al., 2010), with significant amounts of U also present in or associated with REE-enriched mineral deposits (USEPA, 2012). These processing difficulties and complexities are indicative of the risk factors inherent in REE exploration, mining, and processing, which have previously hindered the economic development of potential REE resources.

Here, we present a quantitative global REE dataset based on mineral resources reported using various statutory reporting standards, geologic studies, and government assessments, and use these data to provide an overview of differing REE mineral deposit types, tonnages, TREO + Y concentrations, principal mineralogies, individual REE concentrations, and significant by-/co-products or impurities. This dataset provides a basis for the quantitative analysis of the opportunities, challenges, and uncertainties inherent within the global REE supply chain.

Methodology

REE deposit types and mineralogy

Understanding REE mineral deposit types and the mineralogy of potential REE deposits is crucial for exploration targeting and determining the feasibility of mining operations, processing, and refining. Therefore, we have classified our database using a range of differing mineral deposits types; this classification was first published by Weng et al. (2013) and has been expanded and slightly adapted to reflect the range of known REE deposits. Our classification is obviously a simplification of the natural complexity of REE deposits, which has led to the formulation and implementation of numerous other classification schemes; for example, the United States Geological Survey (Long et al., 2010) classification splits REE deposits into a total of 34 different types of mineral deposits, whereas the British Geological Survey (Walters et al., 2010) uses a simpler split of primary deposits of igneous and hydrothermal origin or secondary deposits concentrated by sedimentary processes and weathering. Here, we consider both the geologic processes involved in the formation of REE deposits and the mineralogy of individual deposits in our classification scheme (shown in Table 2). This classification splits REE deposits into three broad categories relating to the dominant processes that formed the REE mineralization (i.e., igneous, hydrothermal, or secondary/sedimentary processes), before further subdividing into 14 subclassifications (carbonatite, alkaline complexes and pegmatites, felsic volcanic, granites and granitic pegmatites, iron oxide copper-gold (IOCG), granite-related skarn, carbonatite-related skarn,

hydrothermal undifferentiated, heavy mineral sands (HMS), laterites/soils/clays, tailings, shale hosted, alluvial/placer, and sedimentary undifferentiated deposits) that are used to classify individual mineral deposits within our database. It should be noted that this classification, as with all mineral deposit-type classifications, is reliant on the amount of information available, as epitomized by the world's most important REE deposit at Bayan Obo; the formation of this REE deposit is still controversial (e.g., Yang and Le Bas, 2004; Yang et al., 2011; Smith et al., 2015) and, thus, we can only rely on current knowledge and the geologic evidence available within both published and industry literature (e.g., NI43-101 reports) to classify the deposits within our database. In addition, as is often the case for mineral deposits (e.g., Jowitt et al., 2013a), a given mining camp or even resource may contain two or more REE deposit types (Jones et al., 1996; Lai and Yang, 2013; Weng et al., 2013); where this is the case, we have classified a given deposit by the dominant (i.e., most contained REE) deposit type. Several of the hydrothermal deposits in our database are of uncertain origin but are definitively linked with magmatic bodies; we have classified these as skarns, although this terminology may not be strictly correct. Finally, a few of the deposits in our database have definitive hydrothermal or sedimentary origins but could not be classified further, either as a result of a lack of research or because the deposits themselves were poorly understood; these remain classified simply as hydrothermal or sedimentary undifferentiated within our database. We have also classified the Hangaslampi resource as hydrothermal and undifferentiated because, although the deposit is an orogenic gold deposit that also contains Co,

TABLE 2. Classification of REE Mineral Deposit Types Used During This Study[1]

Process	Mineral deposit type		Key examples
Igneous	Silica undersaturated	Carbonatite	Bayan Obo, China; Araxá, Brazil; Karonge, Burundi; Mountain Pass, USA; Nolans Bore, Australia; Steenkampskraal, South Africa
		Alkaline complexes and alkaline pegmatites	Khibina and Lovozero, Russia; Norra Kärr, Sweden; Bokan, USA; Thor Lake, Canada; Kipawa Lake, Canada; Kola Peninsula, Russia
	Silica saturated to oversaturated	Felsic volcanic	Round Top, USA; Foxtrot, Canada
		Granites and granitic pegmatites	Khibina Massif, Russia; Motzfeldt, Greenland; Ytterby, Sweden
Hydrothermal	Iron oxide copper-gold (IOCG)		Olympic Dam, Australia; Milo, Australia
	Skarn	Granite related	Mary Kathleen, Australia
		Carbonatite related	John Galt, Australia; Saima, China
	Undifferentiated		Mount Gee, Australia
Secondary/sedimentary	Heavy mineral sands (HMS)		WIM150, Australia; monazite stockpile in India (IREL)
	Laterite/soil/clay		Tantalus, Madagascar
	Tailings		Steenkampskraal, South Africa; Port Pirie, Australia; Mary Kathleen, Australia
	Shale hosted		Buckton, Canada
	Alluvial/placer		Charley Creek, Australia; India; Sri Lanka; Florida, USA
	Undifferentiated		Korella, Australia

[1] Adapted from Weng et al. (2013)

the nature and association of the REE with this mineralization remain unclear—especially as, although the Co and Au resources within this deposit are reported according to the JORC code, the grade and tonnage of the REE within this deposit remain conceptual and are not currently code compliant. This lack of code compliance for the REE resource within this project also means that this deposit REE resource has a low confidence rating. The next section provides a brief outline of the differing categories and processes involved in REE deposit formation, and the reader is referred to Weng et al. (2013) and references therein for more detailed descriptions.

The REE are highly incompatible in the majority of magmatic systems, meaning that these elements are concentrated in magmas that form as the result of low-degree partial melting of the mantle; this is especially true of metasomatically enriched regions of the mantle that may contain higher concentrations of the REE compared to those expected for typical primitive mantle. The incompatibility of the REE means that low-degree partial melts can contain very high concentrations of these elements (e.g., Chakhmouradian and Zaitsev, 2012; Jordan et al., 2015), although this also means that these elements can be concentrated during significant fractionation or differentiation, with the REE eventually crystallizing out as REE minerals during late-stage fractionation, rather than within earlier fractionated minerals (e.g., Medlin et al., 2015)—a process that can also lead to the formation of volatile-rich pegmatitic magmas. This means that the majority of igneous REE deposits are related either to rock formed from magmas generated by very low degree partial melting (and other associated processes) or by extreme fractionation. Igneous rocks with high REE concentrations, such as carbonatites or alkaline igneous complexes, also form ideal sources for REE-enriched hydrothermal fluids, leading to several REE deposits that contain both primary igneous and hydrothermal REE mineralization (e.g., Bayan Obo).

The REE are thought to be generally immobile during the majority of hydrothermal processes, indicating that the mobilization and the effective deposition and concentration of these elements may require atypical hydrothermal activity. In addition, our hydrothermal REE deposit classification considers very high temperature systems that are, for example, associated with the formation of pegmatites to fall within the igneous category of deposits. Both high-temperature magmatohydrothermal and F- and Cl-bearing hydrothermal systems are frequently associated with the formation of REE-enriched hydrothermal mineralization and hydrothermal REE mineral deposits, although the two systems are not mutually exclusive (e.g., Williams-Jones et al., 2012; Jowitt et al., 2013b; Weng et al., 2013). These systems are thought to dominate the formation of hydrothermal REE deposits, as (1) the REE are more soluble in high-temperature hydrothermal fluids than lower-temperature fluids (Williams-Jones et al., 2012) and (2) hydrothermal fluids that contain significant amounts of F, Cl, and Li ligands can also mobilize significant amounts of the REE, in addition to elements such as U that are often associated with the REE (e.g., McPhie et al., 2011; Williams-Jones et al., 2012), although the exact role of F in the mobilization of the REE and the formation of REE mineral deposits remains contentious (e.g., Skirrow et al., 2007; McPhie et al., 2011; Williams-Jones et al., 2012; Ernst and Jowitt, 2013). Both

high-temperature and high-F and -Cl hydrothermal fluids most likely deposit their REE during interaction with cooler and pH-neutralizing rocks or fluids (e.g., Williams-Jones et al., 2012), although REE deposition may not always be synchronous with the deposition of other metals, such as Cu, Au, or U—as, for example, may be the case at the Hangaslampi deposit, as discussed above.

The fact that REE-bearing minerals are often somewhat denser than most silicate minerals (although not to the same extent as, say, native Au or sulfide minerals) and are refractory and resistant to both alteration and weathering means that they are often preferentially concentrated into sedimentary or secondary deposits during erosion, transportation, and deposition. This has led to the formation of a diverse range of sedimentary (e.g., shale-hosted REE deposits), secondary (e.g., laterite), or placer (e.g., alluvial deposits)-type REE deposits, with the latter two types of deposit containing REE mineralization that is often associated with other dense, refractory minerals (e.g., zircon, rutile, and ilmenite). Although both placer and HMS deposits may result from similar geologic processes, the minerals they target may differ significantly. For example, placer REE deposits like Charley Creek dominantly target REE-enriched minerals such as monazite and xenotime, whereas HMS operations usually target ilmenite, rutile, and zircon, and may produce monazite as a by-product. Hence, placer REE and HMS deposits have very different REE production potentials, meaning that we separate these deposits into two differing classification categories. Our placer category also includes ancient paleoplacer deposits that have been upgraded by postdepositional hydrothermal or metamorphic activity, but anthropogenic secondary placer or tailings deposits, such as the REE-enriched tailings resource at Mary Kathleen, which formed as a result of mining of primary skarn mineralization, have been classified as a separate tailings category within the overall secondary/sedimentary class of REE deposits (Table 2).

REE mineral deposits host a wide and diverse range of REE-bearing minerals, the most economically important of which are bastnäsite, monazite, and xenotime. These are just three of the more than 200 minerals known to contain essential or significant amounts of the REE (Jones et al., 1996; Christie et al., 1998; Hoatson et al., 2011), all of which form as a result of a wide range of geologic processes and, thus, are found in a diverse range of igneous, sedimentary, and metamorphic rocks. This means that understanding the processes that form these mineral deposits and their REE-bearing minerals is crucial not only for exploration but also for designing and operating ore processing routes as well as REE processing facilities (International Atomic Energy Agency [IAEA], 2011a). Given this, we also have classified the REE deposits in our compilation by the dominant REE mineral or minerals within the deposit; as with the mineral deposit classification outlined above, individual deposits may contain a range of undisclosed REE minerals, but our classification focuses on publicly available information taken either from statutory mining code-based reports or from previously published geologic research.

Mineral Resource Accounting

Global REE production has long been dominated by carbonatite or weathered carbonatite deposits, such as Bayan

Obo in China, Mountain Pass in the United States, and Mount Weld in Australia. However, as discussed above, various types of mineral deposits, including alkaline complexes and pegmatites (e.g., Tanbreez in Greenland, Strange Lake in Canada), felsic volcanic rocks (e.g., Round Top in the United States), shale-hosted (e.g., the Grande-Vallée complex and Buckton in Canada), and HMS (e.g., WIM 150/200 in Australia and monazite stockpiles in India) deposits, can contain significant amounts of REE mineral resources and could potentially become major REO producers. The mineralogy, grades, tonnages, and mineral processing used in the exploitation of all these REE deposits have not been systemically analyzed in the literature to date, and each deposit type contains different concentrations of the individual REE and differing proportions of the LREE and the HREE, further complicating the issue of refined REO production. The increasing demand for the REE has also accelerated exploration and the push for extraction from all differing types of REE deposits, either as a target commodity or as a by-product of other elements, such as Fe, Nb, Zr, Ti, and U.

In order to justify the economic feasibility and planning of a mineral deposit, mining companies commonly use statutory codes for assessing and reporting mineral resources, with Australia using the Joint Ore Reserves Committee (JORC) Code (Stephenson, 2001; Australasian Institute of Mining and Metallurgy [AusIMM] et al., 2012), Canada using the CIM code and National Instrument 43-101 (NI 43-101; Ontario Securities Commission [OSC], 2011), South Africa using the South African Mineral Resource Committee (SAMREC) code (South African Mineral Resource Committee Working Group [SAMRCWG], 2009), and similar codes or standards existing in the United States, China, Russia, and Europe. In 1994, the Committee for Mineral Reserves International Reporting Standards (also known as CRIRSCO) established an international standard on mineral reserve-resources reporting, with current members of CRIRSCO including Australia, Canada, Chile, Europe, Russia, South Africa, and the United States.

As discussed by Mudd et al. (2013a) and others, there are two primary categories used to classify a mineral deposit: ore reserves and mineral resources. Ore reserves typically have a high probability of profitable production and can be the basis of a technically and economically viable project, whereas mineral resources have reasonable uncertainties within certain modifying factors (e.g., mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social implications, governmental policy, etc.) for eventual economic extraction (e.g., AusIMM et al., 2012). Common definitions include the following:

1. Ore reserves: Assessments demonstrate at the time of reporting that profitable extraction could reasonably be justified. Ore reserves are subdivided, in order of increasing confidence, into probable ore reserves and proved ore reserves.

2. Mineral resources: The location, quantity, grade, geologic characteristics, and continuity of a mineral resource are known such that there are reasonable prospects for eventual economic extraction, although not all modifying factors have been assessed and, hence, some uncertainty remains. Mineral resources are subdivided, in order of increasing geologic confidence, into inferred, indicated, and measured categories. An inferred mineral resource, where geologic evidence is sufficient to imply but not verify geologic and grade (or quality) continuity, has a lower level of confidence than is inherent within measured or indicated mineral resources and, therefore, cannot be directly converted to ore reserves. It is reasonably expected that the majority of inferred mineral resources could be upgraded to indicated mineral resources with continued exploration (AusIMM et al., 2012).

Some studies undertaken by various geologic, scientific, and governmental organizations assess global REE resources, summarized in Table 3, with the majority based on regional or global geologic estimates (e.g., Indian Bureau of Miners [IBM], 2014), or are focused on limited mineral resources/mineral reserves assessments for individual countries (e.g., Christie et al., 1998; Hoatson et al., 2011). As such, these assessments cannot provide a realistic and systematic dataset of global REE mineral resources that can be used for predicting the global security of supply of these

TABLE 3. USGS Reserves and Reserves Base Values for the REO, Including Respective National Resource Estimates, and Cumulative REO Production by Country to 2013 (in Mt REO)

Country	Reserves (2008)[1]	Reserves (2010)	Reserves (2013)	Reserves (2014)	National resource estimate	Cumulative REO production
USA	13	13	13	1.8	ND	0.56
Australia	5.2	1.6	2.1	3.2	58[2]	0.16
Brazil	0.05	0.05	22	22	ND	0.012
China	27	55	55	55	182[3]	2.04
India	1.1	3.1	3.1	3.1	6[4]	0.077
Malaysia	0.03	0.03	0.03	0.03	ND	0.019
Russia and Commonwealth of Independent States	19	19	ND	ND	ND	0.061
Other	22	22	41	41	ND	0.007
Total[5]	88[5]	110[5]	140[5]	130[5]		2.94

Notes: Reserves from USGS (1997–2015); ND = no data
[1]Reserves base in 2008 was 150 Mt REO, suggesting an additional 62 Mt REO to the reserves
[2]Total mineral resources estimate for Australia (Britt et al., 2015)
[3]National resource estimate for China is from CSRE (2002)
[4]India assumes 60% REO from reported monazite resources from IBM (2014); historical Australian production is from BoMRGG (1960–1985) with an assumed 60% REO conversion rate from reported monazite production
[5]Totals rounded down to two significant figures

critical elements. The most widely cited group that publishes such estimates is the USGS, which publishes approximate reserve estimates for numerous metals and minerals in its annual *Mineral Commodity Summaries* (USGS, 1997–2015). Recent estimates of REO reserves, mineral resources (depending on source organization), and annual and cumulative production (see Table 3) suggest global REO reserves of about 130 Mt in 2014. In reality, mining companies tend to demonstrate an ore reserve of a mining project using the minimal investment required to justify its profitability. However, given that ore reserves are determined by a range of compulsory "modifying factors" (see above), additional mineral resources that are known but not quantified as reserves are excluded from formal ore reserve estimates. This means that ore reserves generally represent only a small part of an often continuous orebody, with long-term production planning involving the continual upgrade of mineral resources to ore reserves and then production, commonly as a project is operating (e.g., Jowitt et al., 2013a; Mudd et al., 2013a, b). As summarized in Hellman and Duncan (2014, p. 111), "there are no special issues relating to the mechanics of the estimation of REE mineral resources which appear similar in mineralization style to primary and supergene enriched Cu deposits," meaning that all categories of REE mineral resources could potentially contribute to future REE reserves, as has been documented by previous research (e.g., Jowitt et al., 2013a; Mudd et al., 2013a, b).

In order to realistically analyze the long-term prospects for global recoverable REE, this study focuses on REE mineral resources that include all measured, indicated, and inferred resources by individual projects or deposits reported under statutory codes or other robust technical literature. In addition, resources based on the former and the latter are clearly differentiated by assessing and quantifying the reliability of these data. However, the complexities in REE mineralization and the somewhat limited global scale of REE mining mean that significant variations exist within current REE resource reporting. For example, company reports that comply with the CIM reporting code and NI 43-101 usually provide details of mineral deposit types, REE mineralogies, TREO + Y concentrations, LREE/HREE fractions, and orebody tonnages, whereas JORC code-based projects typically only report orebody tonnages and TREO + Y concentrations. Therefore, we have compiled information from other sources, including the technical literature and published peer-reviewed articles, to provide sufficient detail on each deposit to ensure the dataset presented here is as comprehensive as possible. Furthermore, the fact that there are numerous deposits that contain significant amounts of the REE that are not formally reported (e.g., Olympic Dam) means that some of the data in our compilation are based on the best available code-noncompliant data from the technical literature. Taking into account the uncertainties inherent in combining these different sources of REE mineral resource data, we divided our dataset into three different categories of reliability using the approach outlined in Mudd et al. (2013b):

1. High: Tonnage and TREO + Y concentrations are provided by reporting code-compliant data (e.g., JORC, CIM/NI 43-101, SAMREC, etc.).

2. Medium: Tonnages are reported as code-compliant data, with TREO + Y concentrations provided through additional code-noncompliant technical information.

3. Low: Information is derived from government reports or from other technical literature with code-noncompliant data.

From a production perspective, REE minerals are extracted as target or important commodities through conventional mining operations (e.g., Mountain Pass) but are also produced as by-/co-products from various sources, including base metal mining (e.g., iron production in Bayan Obo, China), HMS mining (e.g., monazite production in India), loparite mining (e.g., Lovozero, Russia), and so on. In addition, the REE could potentially be extracted as a by-product of phosphate mineral production (e.g., Araxá, Brazil), U mining (Mary Kathleen, Australia), and deep-sea mining (e.g., Kato et al., 2011).

Monazite is one of the most significant REE minerals in terms of potential REO production, is a relatively minor constituent (commonly ≤2% of the contained total heavy minerals) of many HMS deposits, and is usually treated as an impurity during titanium mineral (primarily ilmenite, rutile, and leucoxene) and zircon production (IAEA, 2011a). As shown in Figure 1, Australia produced monazite concentrates containing a minimum of 60% contained REO (Bureau of Mineral Resources, Geology and Geophysics [BoMRGG], 1960–1985) up to the mid-1990s, and became the largest monazite producer in the world in 1985, producing some 18,735 t of monazite (BoMRGG, 1960–1985). Although the Australian HMS industry does not currently export monazite for REO production (Australian Safeguards and Non-Proliferation Office [ASNO], 2014), the significant amounts of REO present in currently exploited and known HMS deposits and projects could become an important future source of the REE. Other countries like China, India, Russia, and Canada also have similar potential in terms of REO production from monazite extracted from placer, HMS, or hard-rock deposits. It should be noted that variations in geologic setting and formation processes mean that the TREO + Y concentrations within monazite in individual monazite-dominant deposits vary significantly, from an average of 35% in Vietnam (IAEA, 2011a) to 71% (Long et al., 2010). However, monazite contains significant amounts of Th, meaning that any REO produced from this material may leave a radioactive residue, although the concentration of Th (reported as a single element rather than as an oxide) within monazite also varies between 1.2% and 21.9% (van Emden et al., 1997; Hoatson et al., 2011). Here, we estimate the potential REO resources contained in HMS projects using a moderate but robust assumption that the monazite within all reported monazite resources in our database contains 55% TREO + Y and 7% Th.

In addition, a significant amount of potential REE resources (e.g., deep-sea REE mining, nuclear reprocessing, electronic waste recycling, etc.) have not yet been systematically studied or reported as a consequence of lack of exploration and the targeting of other elements rather than the REE as the main commodity to be exploited in a given deposit/prospect. Some REE projects also do not report any code-compliant data and, thus, cannot be considered to be equivalent to mineral resources and have been excluded from our dataset. For example, the Jongju deposit in North Korea is claimed to

include some 216.2 Mt of contained TREO resources (Pacific Century Rare Earths Minerals Limited [PCREML], 2012), but this reporting is not code based or compliant with any other technical standard for quantifying mineral resources. This, combined with the fact that very little is known about this controversial purported deposit, means that we have deliberately excluded it from our dataset. Furthermore, some past REO producers have not been systemically analyzed and reported (e.g., placer/HMS-derived monazite production in Sri Lanka or monazite from tin mining in Malaysia); these uncertainties mean that, although these resources probably exist, quantifying them with any degree of certainty remains impossible, and they have therefore not been included in this paper.

The compiled data presented in this study should therefore be considered a minimum estimate of current global REE resources, especially as the majority of the resources within our database are from code-based reporting or are derived from the best available code-noncompliant data from the literature and published peer-reviewed articles (as undertaken by Mudd et al., 2013a, b). We have also provided the full dataset, including resources for individual REE deposits, as supplementary information to this paper.

Results and Analysis

Our minimum estimate of global REO mineral resources is given in Table 4, with resources split by country given in Table 5. It should be noted that our overall database includes seven projects for which only total contained REO tonnages were available (HMS deposits in Andhra Pradesh, Bihar, Kerala, Odisha, Tamil Nadu, and West Bengal in India and the ion-adsorption clay deposits of the southern seven provinces of China); these projects are included in our overall REO resource calculations but are not included in any other calculations. Our compilation indicates that current global REO resources stand at 619.5 million tonnes (Mt) TREO + Y within 267 deposits, with the 260 deposits that have reported tonnage and grade data including 88,483 Mt of mineral resources at an average TREO+Y grade of 0.63%; this is further split into 111, 199, and 310 Mt TREO + Y in 65, 126, and 76 deposits within high-, medium-, and low-reliability categories, respectively. Current TREO + Y resources are dominated by the LREE, with an average light REO (LREO; La-Gd) to heavy REO (HREO) + Y (Tb-Lu and Y oxides) ratio of 13:1, although it should be noted that the HREO here include Y, which is much more abundant than HREE such as Lu and Tb. Splitting the resources in our database by individual country indicates that

China dominates known contained REO resources, with some 43% of global REO resources (268.1 Mt TREO + Y), followed by Australia, Russia, Canada, and Brazil with resources of 64.5, 62.3, 48.3, and 47.1 Mt contained TREO + Y, respectively. These results significantly exceed the current estimates of global REO reserves from the USGS (although our data are resource rather than reserve based) and the various national resource estimates that are summarized in Table 3.

In terms of principal deposit types, the majority of the current global REO resources are hosted by carbonatites, which contain some 318.6 Mt of TREO + Y within 67 individual projects. In addition, a further 84.3, 80.5, 60.3, 53.9, and 12.4 Mt of TREO + Y resources are hosted by tailings, alkaline complexes and pegmatites, laterite/soil/clay, IOCG, and HMS deposits, with an additional 9.5 Mt in other categories. However, it should be noted that REO resource estimates within several deposit-type categories (e.g., tailings, laterite/soil/clay, and IOCG) are biased by the presence of one or two giant projects within each category; for example, the Bayan Obo tailings alone contains 83 out of a total of 84.3 Mt contained TREO + Y in our tailings category, and 53 Mt of the total 53.9 Mt TREO + Y within IOCG deposits is within the Olympic Dam project. In both cases, these REO resources have been classified as low-reliability data, further indicating the lower reliability of the resource estimates within these categories.

The relationship between TREO + Y grades and mineral resources for various deposit types is illustrated in Figure 2. Carbonatite deposits dominate ore grades and contained REO whereas other deposit types, such as alkaline complexes and pegmatite, alluvial and placer deposits, and felsic volcanic rocks, have moderate REE grades but highly variable total mineral resources, and HMS and shale-hosted projects are typically low grade but bulk tonnage ($\geq$1,000 Mt).

Figure 3 illustrates the relationship between TREO + Y grades and principal REE mineralogy, with the ionic clay classification in this diagram including both deposits with REE resources associated with ion-adsorption clays and shale-hosted deposits that have REE mineralogies dominated by clay minerals. Global REO production is dominated by bastnäsite extraction (e.g., Bayan Obo, Mountain Pass), with bastnäsite-based REE projects also having the highest average TREO + Y concentration of 3.27%, although the tonnages of all of these deposits vary significantly. Monazite-based REE projects have the most significant variations in both tonnage and grade, with some hard-rock monazite projects (e.g., Tomtor, Steenkampskraal, etc.) having TREO + Y grades >10%, but the majority of monazite-based HMS projects have average TREO + Y grades of 0.01%. Furthermore, these HMS projects tend to contain significant amounts of mineral resources (>1,000 Mt) but have low to very low TREO + Y grades that reflect the importance of other non-REE minerals (e.g., ilmenite, rutile, and zircon) in these deposits (<0.1% TREO + Y).

Cumulative frequency curves for TREO + Y concentrations and contained TREO + Y tonnages are given in Figure 4. The median size of the 260 REE deposits with grade and tonnage data in our database is 0.04 Mt TREO + Y at a median grade of 0.23% TREO + Y. Some 82% of these projects contain <1 Mt contained TREO + Y, with 4% of the deposits in our database containing >10 Mt TREO + Y, indicating the

TABLE 4. Total REE Mineral Resources by Reliability Classification

Reliability level	Mineral resources (Mt)	Average TREO + Y grades (%)	TREO + Y (Mt)	No. of deposits
High	19,314	0.58	111	65
Medium	45,138	0.44	199	126
Low	24,031	1.01[1]	310	76
Total	88,483	0.63[1]	619	267

[1]Average TREO + Y grade calculation does not include the seven deposits without available grade and tonnage data

TABLE 5. Total Global REO Resources Split by Country and Deposit Type and Listed with Potential By-/Co-products

Country	Deposit type	No. of deposits	Mt ore	% LREO	% HREO + Y	% TREO + Y	REO (kt)	Th (ppm)	U (ppm)	Other metals
Afghanistan	Carbonatite	1	37	NR	NR	3.6	1,334	NR	500	Ba-Sr
Argentina	Carbonatite	1	5.6	NR	NR	2.1	118	NR	NR	NR
Australia	Alkaline complex and pegmatites	2	146	NR	NR	0.39	573	54[1]	NR	Zr-Nb-Ta
	Alluvial/placer	1	805	0.020[1]	0.010[1]	0.029	235	NR	NR	NR
	Carbonatite	11	78	7.7[2]	0.21[2]	3.3	2,533	41[1]	148[1]	Fe-P-Al
	Carbonatite-related skarn	1	0.05	NR	NR	0.35	0.18	NR	NR	NR
	Felsic volcanic	1	36	0.040	0.17	0.21	76	NR	NR	NR
	Granite-related skarn	5	54	2.236	0.11	2.4	1,264	27[4]	153	Zr-Nb-Hf
	Hydrothermal undifferentiated	1	44	NR	NR	0.12	53	NR	509	NR
	IOCG	2	9,763	0.049[1]	0.010[1]	0.55	53,810	NR	2,20[1]	Cu-Fe-Au
	Sedimentary undifferentiated	1	14	NR	NR	0.07	9.6	NR	NR	NR
	Tailings	2	5.7	0.65[1]	0.32[1]	6.3	354	NR	159	NR
	Heavy mineral sands	83	18,275	0.0012[1]	0.00[1]	0.029	5,611	34[83]	NR	Ti-Fe- Zr
	Subtotal	110	29,221	0.15[12]	0.010[12]	0.22	64,519	34[88]	295[10]	
Brazil	Carbonatite	5	3,338	4.1[1]	0.070[1]	1.4	47,111	NR	NR	Al-Fe-P-Nb
Canada	Alkaline complex and pegmatites	6	991	0.81[5]	0.24[5]	0.96	9,499	226[4]	49[2]	Al-Fe-Ga-Ta-Zr-Be-Hf
	Alluvial/placer	3	160	0.13	0.0084	0.14	227	245[2]	416	Sc
	Carbonatite	7	2,470	1.5[6]	0.049[6]	1.5	36,551	377[3]	NR	Nb-Fe-Mn
	Felsic volcanic	1	14	0.83	0.18	1.0	146	NR	NR	Zr-Nb
	Shale hosted	3	6,249	0.13[2]	0.010[2]	0.031	1,915	10[2]	9[2]	Zn-Cu-Co-V-Ni-Mo-Sc-Li-Si-Mg
	Subtotal	20	9,884	0.49[17]	0.038[17]	0.49	48,338	71[11]	24[7]	
China	Carbonatite	6	1,614	5.9[1]	0.058[1]	7.6	122,591	334[1]	NR	Nb-Fe-F
	Laterite/soil/clay	1	NR	NR	NR	NR	59,900	NR	NR	NR
	Tailings	1	1,200	NR	NR	7.0	83,400	378[1]	NR	Nb-Fe-F
	Shale hosted	1	4,400	NR	NR	0.05	2,200	NR	NR	NR
	Subtotal	9	9,070	5.9[1]	0.058[1]	2.3[1]	268,092	353[2]	NR	
Finland	Alkaline complex and pegmatites	1	0.46	NR	NR	1.1	11	1,200	250	Nb-Zr
	Carbonatite	1	0.86	NR	NR	0.71	7	NR	NR	Pb
	Hydrothermal	1	0.60	NR	NR	0.022	0	NR	100	Co-Au
	Subtotal	3	2	NR	NR	1.2	18	1,200[1]	220[2]	
Gabon	Carbonatite	1	380	NR	NR	2.5	9,576	NR	NR	Nb
Germany	Carbonatite	1	4.4	NR	NR	0.45	20	NR	NR	NR
Greenland	Alkaline complex and pegmatites	6	5,622	0.56	0.14	0.70	39,512	232[3]	NR	Nb-Zr-Ta
	Carbonatite	1	12	1.4	0.010	1.4	176	NR	NR	NR
	Subtotal	7	5,635	0.57	0.14	0.70	39,688	232[3]	NR	
India	Alluvial/placer	1	104	NR	NR	1.5	1,549	NR	NR	NR
	Carbonatite	1	12	NR	NR	1.1	123	NR	NR	NR
	Heavy mineral sands	6	NR	NR	NR	NR	5,885	NR	NR	NR
	Subtotal	8	115	NR	NR	1.4[1]	7,557	NR	NR	NR
Kenya	Carbonatite	2	163	3.6[1]	0.27[1]	3.9	6,286	450[1]	26[1]	Nb
Kyrgyzstan	Alkaline complex and pegmatites	1	18	0.15	0.11	0.26	47	NR	NR	NR
	Carbonatite	1	7	NR	NR	0.20	14	NR	NR	NR
	Granites and granitic pegmatites	2	16	NR	NR	0.98	157	NR	NR	NR
	Subtotal	4	41	0.15[1]	0.11[1]	0.53	217	NR	NR	Nb
Madagascar	Laterite/soil/clay	1	435	0.067	0.014	0.08	351	44	8	Zr-Nb-Ga-Sn-Ta
Malawi	Carbonatite	4	63	1.2[2]	0.070[2]	1.4	867	297[1]	12[1]	P, Nb
Mauritania	Carbonatite	1	0.1	NR	NR	4.4	4	NR	NR	NR
Mongolia	Alkaline complex and pegmatites	1	425	NR	NR	0.40	1,713	NR	NR	NR
	Carbonatite	2	368	NR	NR	1.6	5,895	NR	NR	NR
	Subtotal	3	793	NR	NR	0.96	7,608	NR	NR	NR
Mozambique	Carbonatite	1	1.1	NR	NR	2.1	23	NR	NR	P-Nb
	Heavy mineral sands	9	8,145	NR	NR	0.009	758	NR	NR	Ti-Fe-Zr
	Subtotal	10	8,146	NR	NR	0.015	781	NR	NR	
Namibia	Carbonatite	1	8	NR	NR	3.0	240	NR	NR	NR
Norway	Alkaline complex and pegmatites	3	87	NR	NR	0.25	219	490[1]	NR	Nb-Zr-Ta
	Carbonatite	1	486	NR	NR	0.90	4,374	NR	NR	NR
	Granites and granitic pegmatites	3	104	NR	NR	0.13	131	NR	NR	NR
	Hydrothermal undifferentiated	1	0.050	NR	NR	0.20	200	NR	900[1]	Sc
	Subtotal	8	677	NR	NR	0.72	4,924	490[1]	900[1]	
Peru	Heavy mineral sands	2	1,329	NR	NR	0.010	125	NR	NR	NR
Russia	Alkaline complex and pegmatites	18	5,259	NR	NR	0.52	27,145	NR	NR	P-Nb-Ta
	Carbonatite	2	605	NR	NR	5.8	35,199	NR	NR	Zr-Nb
	Subtotal	20	5,864	NR	NR	1.1	62,344	NR	NR	
Saudi Arabia	Alkaline complex and pegmatites	5	439	0.060	0.16	0.20	911	415	113	Zr-Nb-Sn-Ta

TABLE 5. (Cont.)

Country	Deposit type	No. of deposits	Mt ore	% LREO	% HREO + Y	% TREO + Y	REO (kt)	Th (ppm)	U (ppm)	Other metals
South Africa	Carbonatite	4	6,444	1.8	0.10	0.17	10,847	25,291[1]	506[1]	Nb-Sc-P
	Tailings	3	297	6.4[2]	0.56[2]	0.15	448	NR	NR	NR
	Alkaline	2	14	16[1]	1.0[1]	1.19	165	NR	NR	NR
	Subtotal	9	6,755	1.82[5]	0.10[6]	0.17	11,461	25,291[3]	506[3]	
Sweden	Alkaline complex and pegmatites	1	58	0.31	0.27	0.59	341	10	10	Zr-Hf
	Alluvial/placer	1	12	0.35	0.15	0.50	62	NR	NR	NR
	Shale hosted	1	200	NR	NR	0.11	220	NR	NR	NR
	Subtotal	3	271	0.32[2]	0.25[2]	0.23	624	10[1]	10[1]	
Tanzania	Carbonatite	2	198	2.2[1]	0.019[1]	2.3	4,505	NR	NR	NR
Turkey	Alkaline complex and pegmatites	3	530	0.060[2]	0.010[2]	0.071	402	34[2]	7[2]	Fe-Ti-Ga
	Carbonatite	1	30	NR	NR	3.1	942	NR	NR	NR
	Subtotal	4	560	0.060[2]	0.010[2]	0.24	1,344	34[2]	7[2]	
USA	Alkaline complex and pegmatites	2	31	0.37[1]	0.21[1]	0.26	78	73[1]	58[1]	Zr-Nb
	Alluvial/placer	1	18	NR	NR	0.08	14	NR	NR	NR
	Carbonatite	7	2,643	4.0[2]	0.050[2]	0.54	14,140	44[2]	12[2]	NR
	Felsic volcanic	1	1,034	0.020	0.040	0.064	662	NR	NR	NR
	Granite-related skarn	2	6	NR	NR	1.2	71	NR	NR	NR
	Granites and granitic pegmatites	1	0.05	NR	NR	8.6	4	NR	NR	NR
	Hydrothermal undifferentiated	2	128	NR	NR	0.37	476	NR	NR	NR
	Tailings	1	9	0.65	0.24	0.89	80	NR	NR	NR
	IOCG	2	0.6	NR	NR	12	72	NR	NR	NR
	Subtotal	19	3,861	0.27[5]	0.050[5]	0.40	15,621	44[3]	12[3]	
Vietnam	Carbonatite	2	1,057	NR	NR	1.4	14,798	NR	NR	NR
Zambia	Carbonatite	1	130	NR	NR	0.30	390	NR	NR	Nb-P
The world	Alkaline complex and pegmatites	51	13,621	0.52[22]	0.14[22]	0.59	80,510	213[17]	122[16]	
	Alluvial/placer	7	1,099	0.050[5]	0.010[5]	0.19	2,087	245[2]	416[3]	
	Carbonatite	68	21,993	3.2[20]	0.060[20]	1.4	318,650	190[9]	20[6]	
	Carbonatite-related skarn	1	0.05	NR	NR	0.35	0.18	NR	NR	
	Felsic volcanic	3	1,084	0.030	0.050	0.081	884	NR	NR	
	Granite-related skarn	7	60	2.2[5]	0.11[5]	2.2	1,335	27[4]	153[5]	
	Granites and granitic pegmatites	6	120	NR	NR	0.24	292	NR	NR	
	Sedimentary undifferentiated	1	14	NR	NR	0.07	10	NR	NR	
	Heavy mineral sands	100	27,747	0.0012[1]	0.00[1]	0.023[1]	12,392	37[82]	NR	
	Hydrothermal undifferentiated	5	173	NR	NR	0.31	529	NR	503[3]	
	IOCG	4	9,774	0.049[1]	0.010[1]	0.55	53,920	NR	220[1]	
	Laterite/soil/clay	2	435[1]	0.067[1]	0.014[1]	0.08[1]	60,251	44[1]	8[1]	
	Shale hosted	5	6,449	0.13[2]	0.010[2]	0.067	4,335	10[2]	16[3]	
	Tailings	7	1,512	0.67[4]	0.24[4]	5.6	84,282	378[1]	159[2]	
	Total	267	88,483	0.93[64]	0.070[64]	0.63[1]	619,477	81[118]	127[40]	

Notes: Superscript numbers in parentheses denote the number of deposits used to derive the LREO-HREO values in this table; these are different from the values for the TREE since all deposits were used for TREO calculations; for example, the two known Australian carbonatite deposits with fully reported REE concentrations were used to to derive the LREO and HREO percentages within the table, but the TREO statistics are based on all 11 deposits, as TREO data are reported for all of these projects; values are rounded down to two significant figures; NR = not reported

[1]Average TREO + Y grade calculation does not include the seven deposits without available grade and tonnage data

importance of these giant deposits in terms of global REE supply both now and in the future. About 68% of the REE deposits in our database have TREO + Y grades <1% whereas 1% of projects have TREO + Y concentrations >10%. The top 25 REE projects by concentrations and contained TREO + Y tonnages are shown in Tables 6 and 7, including concentrations of individual REE and Sc where available. Both of these tables are dominated by carbonatite-hosted REE deposits, suggesting that this deposit type could continue to be the dominant source of the LREE production for the foreseeable future. However, other crucial factors, such as the lack of known HREE resources combined with the high demand for this subset of the REE, hazardous impurities, and processing efficiency, also need to be considered when assessing the global REO supply chain. There are still uncertainties within mineral resource estimates for even the most significant REE projects, which certainly limits a highly accurate assessment

of global REE resources. This is exemplified by the uncertainties surrounding the Bayan Obo deposit, the world's largest REO producer since the mid-1980s, and the ionic clay-hosted REE deposits in the seven southern provinces of China (e.g., Fujian, Guangxi, etc.) that dominate the global supply of the HREE; these projects have only medium- to low-confidence mineral resource estimates, with limited or even no information on their mineralogy and details of the individual REE concentrations within these deposits.

The global distribution of REO resources split by country and by principal deposit types is shown in Figure 5. The TREO + Y resources in our database are led by China, which contains some 43% of known global TREO + Y resources, with lesser amounts in Australia (10%), Russia (10%), Brazil (8%), Canada (8%), Greenland (6%), and the United States (3%); the 57% of global TREO + Y resources outside China are located in 27 different countries, indicating a diverse range of
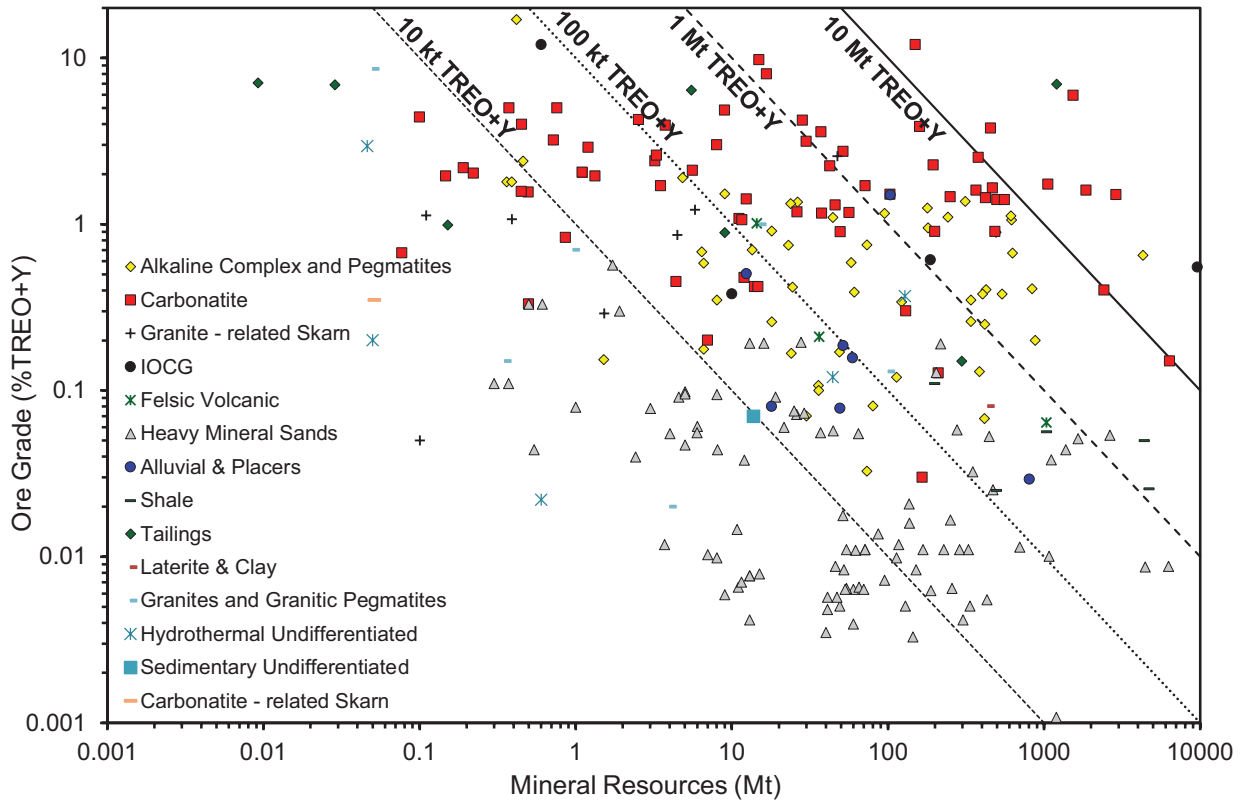
FIG. 2. TREO + Y grades versus mineral resources split by principal REE deposit types.
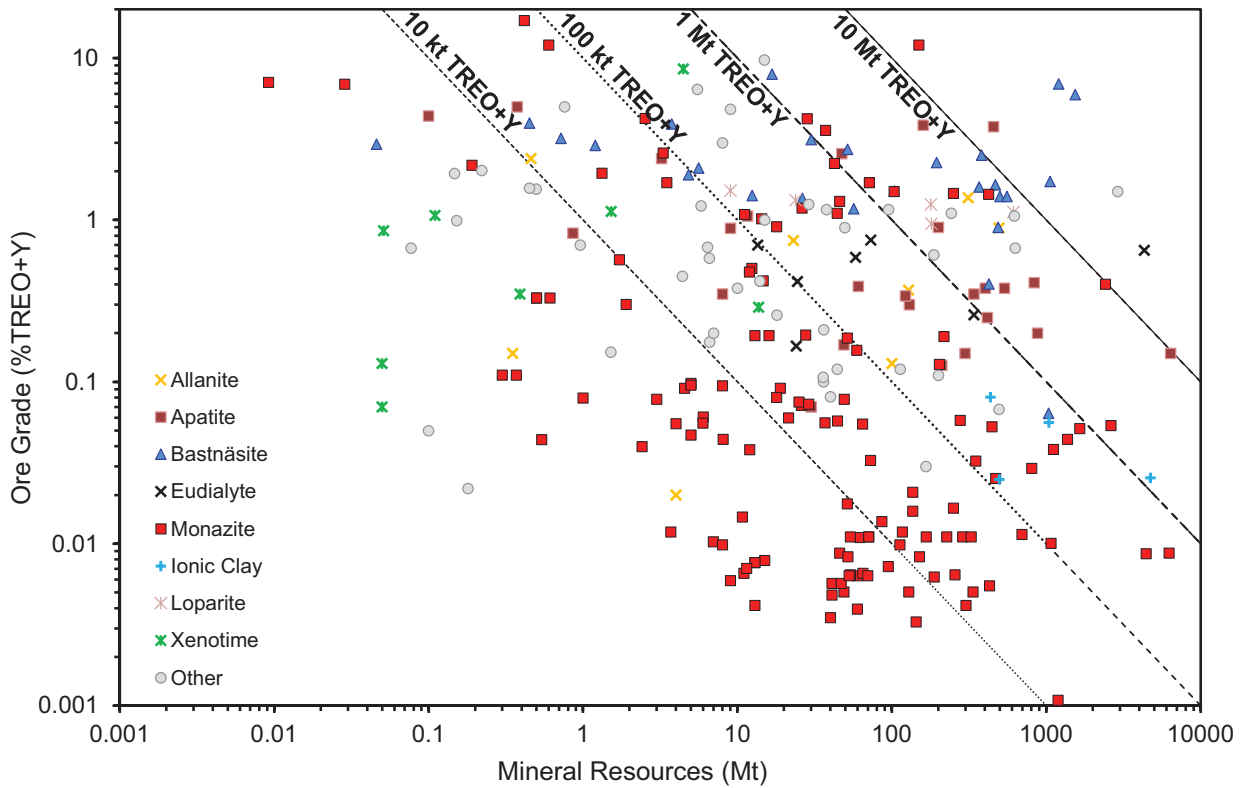
FIG. 3. TREO +Y grades versus mineral resources split by principal REE mineralogy. The ionic clay classification in this diagram includes both deposits with REE resources associated with ion-adsorption clays and shale-hosted deposits that have REE mineralogies dominated by clay minerals
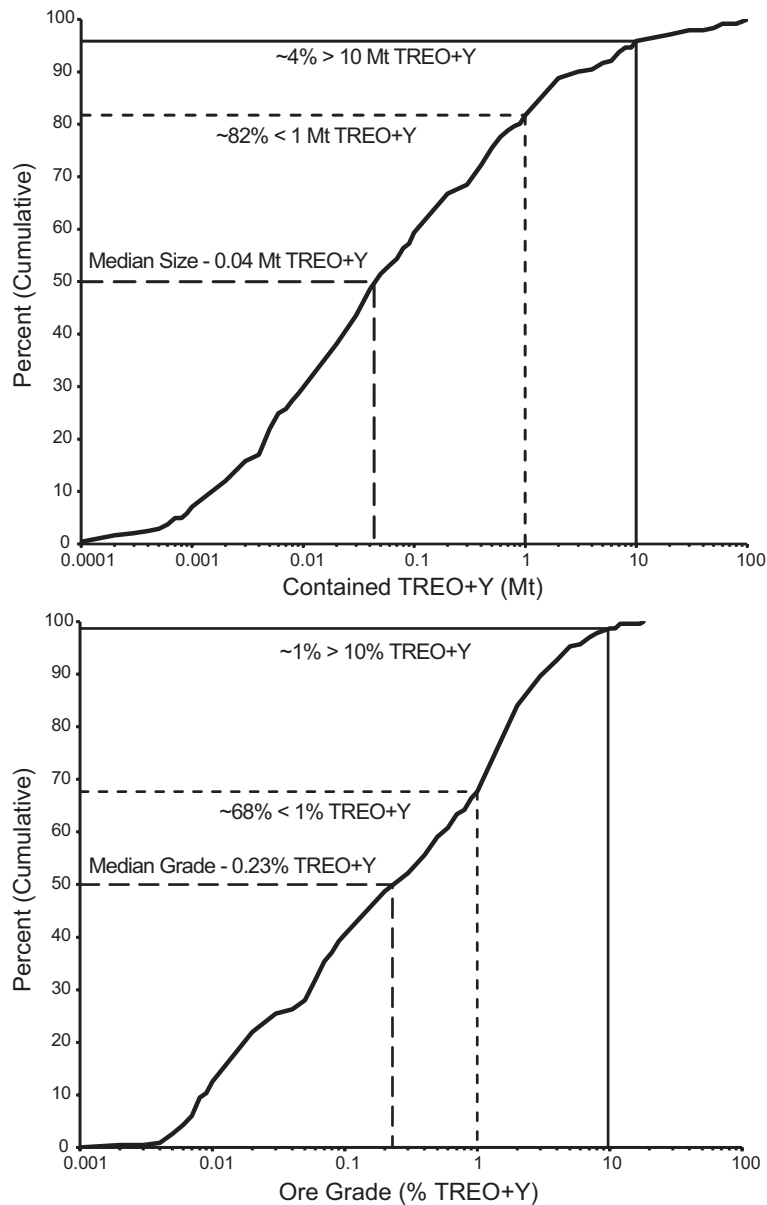
FIG. 4. Cumulative frequency curves for contained total rare earth oxides (above) and ore grades (below).

possible future REE suppliers. The majority of REE deposits are hosted by carbonatites (51.4%), with significant amounts of the REE hosted by tailings (13.6%), alkaline complexes and pegmatites (13.0%), lateritic or clay-related deposits (9.7%), and IOCG deposits (8.7%). However, as discussed previously, these results are heavily skewed by one or two megaprojects in certain categories (e.g., Bayan Obo tailings contain 83 of 84 Mt TREO + Y within the tailings category and Olympic Dam accounts for 53 of 54 Mt TREO + Y in IOCG deposits), making these deposit-type categories seemingly much more attractive for exploration than they actually are.

From a production perspective, each of the individual REE have similar but distinctive chemical characteristics, mineralogies, ore grades, uses, and demands, meaning that each of these elements have differing economic values. This complexity means that traditional economic aspects, such as mineral resources, ore grades, and the size of an orebody, may not be enough to determine the long-term economic feasibility of an REE deposit. This, in turn, means that additional factors, including the relative abundances of the LREE and the HREE and the concentrations of the individual REE within a project, are crucial considerations during economic assessment and operational planning activities associated with REE mining projects. As illustrated in Figure 6 and Table 8, the majority of current reported REE mineral resources with reported individual elemental REE concentrations are LREE dominated, containing especially high concentrations of Ce (~100 Mt contained Ce), La (~55 Mt), and Nd (~24 Mt), whereas HREE resources are dominated by 9.9 Mt Y followed by 1.5 Mt Dy, 0.98 Mt Er, and 0.96 Mt Yb, a distribution that is similar to the relative abundance of these elements in the Earth's crust (e.g., Rudnick and Gao, 2003). The rest of

TABLE 6. The 25 Highest-Grade REE Deposits Listed by TREO + Y Grade and with Splits of Individual REE Concentrations

Project	Country	Principal deposit type	Reliability level	REE mineralogy	TREO + Y (%)	Mineral resources (Mt)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)
Steenkampskraal	South Africa	Alkaline	High	Monazite	17	0.42	30,333	62,532	7,257	26,462	4,156	86	2,881	318	1,442
Tomtor	Russia	Carbonatite	Low	Monazite, pyrochlore	12	150	NR	NR	NR	NR	NR	NR	NR	NR	NR
Pea Ridge	USA	IOCG	Low	Monazite, xenotime, bastnäsite	12	0.60	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mount Weld CLD	Australia	Carbonatite	High	Monazite, rhabdophane, churchite	10	15	19,810	39,497	4,290	15,123	2,047	445	920	76	212
Music Valley	USA	Granite	Low	Xenotime	8.6	0.050	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mountain Pass	USA	Carbonatite	Medium	Bastnäsite	8.0	17	23,003	33,803	2,811	7,639	585	72	145	11	24
Steenkampskraal (Upper Tailings Dam)	South Africa	Tailings	High	Monazite	7.1	0.0092	15,990	18,671	3,745	13,703	2,111	81	1,528	174	860
Bayan Obo (Tailings Dam)	China	Tailings	Low	Bastnäsite, monazite, xenotime	7.0	1,200	NR	NR	NR	NR	NR	NR	NR	NR	NR
Steenkampskraal (Lower Tailings Dam)	South Africa	Tailings	High	Monazite	6.9	0.029	15,433	17,684	3,845	13,375	2,156	86	1,562	174	871
Mary Kathleen	Australia	Tailings	Low	NR	6.4	5.5	NR	NR	NR	NR	NR	NR	NR	NR	NR
Bayan Obo	China	Carbonatite	Medium	Bastnäsite, monazite, xenotime	5.9	1,540	12,628	26,012	2,785	7,943	661	207	310	45	141
Dalucao	China	Carbonatite	Low	NR	5.0	0.76	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chilwa Island	Malawi	Carbonatite	Low	Apatite, bastnäsite, florencite, fluorite, pyrite	5.0	0.38	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mount Weld Duncan	Australia	Carbonatite	High	Rhabdophane, monazite, churchite	4.8	9.0	10,257	16,262	1,963	7,419	1,180	322	835	109	535
Bou Naga	Mauritania	Carbonatite	Low	Apatite, barite, bastnäsite, fluorite, monazite	4.4	0.10	NR	NR	NR	NR	NR	NR	NR	NR	NR
Kangankunde	Malawi	Carbonatite	High	Monazite, bastnäsite	4.2	3.5	10,774	17,991	1,703	5,089	384	70	132	26	296
Araxá	Brazil	Carbonatite	High	Monazite, apatite	4.2	28	10,062	17,742	1,631	4,995	541	122	250	26	105
Muluozhai	China	Carbonatite	Low	Bastnäsite	4.0	0.45	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ruri Complex	Kenya	Carbonatite	Low	Bastnäsite, eudialyte, fluorite, monzite	3.9	3.8	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mrima Hill	Kenya	Carbonatite	High	Apatite, magnetite, barite, fluorite	3.9	159	8,658	14,135	1,428	4,969	697	196	503	62	308
Chuktukonskoye	Russia	Carbonatite	Medium	Apatite (francolite), barite, cerianite, hematite, ilmenite, monazite	3.8	455	NR	NR	NR	NR	NR	NR	NR	NR	NR
Khanneshin	Afghanistan	Carbonatite	Low	Monazite, synchysite, bastnäsite	3.6	37	NR	NR	NR	NR	NR	NR	NR	NR	NR
Lugin Gol	Mongolia	Carbonatite	Low	Bastnäsite, fluorite, parisite, pyrite, rutile, synchysite	3.2	0.72	NR	NR	NR	NR	NR	NR	NR	NR	NR
Kizilcaoren	Turkey	Carbonatite	Low	Bastnäsite, braunite, fluorite	3.1	30	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ondurukurme Complex	Namibia	Carbonatite	Low	Monazite	3.0	8.0	NR	NR	NR	NR	NR	NR	NR	NR	NR

TABLE 6. (*Cont.*)

Project	Country	Principal deposit type	Reliability level	REE mineralogy	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Y (ppm)	Sc (ppm)	LREE (ppm)	HREE (ppm)	LREO (%)	HREO +Y (%)
Steenkampskraal	South Africa	Alkaline	High	Monazite	224	467	45	191	23	5,474	NR	133,708	8,185	16	1
Tomtor	Russia	Carbonatite	Low	Monazite, pyrochlore	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Pea Ridge	USA	IOCG	Low	Monazite, xenotime, bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mount Weld CLD	Australia	Carbonatite	High	Monazite, rhabdophane, churchite	25	51	8.5	26	NR	582	NR	82,132	981	9.6	0.12
Music Valley	USA	Granite	Low	Xenotime	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mountain Pass	USA	Carbonatite	Medium	Bastnäsite	2.8	4.2	1.4	1.4	NR	82	NR	68,059	126	8.0	0.02
Steenkampskraal (Upper Tailings Dam)	South Africa	Tailings	High	Monazite	87	262	25	88	8.8	3,009	NR	55,827	4,514	6.5	0.55
Bayan Obo (Tailings Dam)	China	Tailings	Low	Bastnäsite, monazite, xenotime	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Steenkampskraal (Lower Tailings Dam)	South Africa	Tailings	High	Monazite	87	262	26	26	9	3,071	NR	54,141	4,527	6	0.56
Mary Kathleen	Australia	Tailings	Low	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Bayan Obo	China	Carbonatite	Medium	Bastnäsite, monazite, xenotime	NR	31	NR	91	23	157	NR	50,546	489	5.9	0.06
Dalucao	China	Carbonatite	Low	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chilwa Island	Malawi	Carbonatite	Low	Apatite, bastnäsite, florencite, fluorite, pyrite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mount Weld Duncan	Australia	Carbonatite	High	Rhabdophane, monazite, churchite	80	173	17	76	9	1,969	NR	38,238	2,969	4.5	0.36
Bou Naga	Mauritania	Carbonatite	Low	Apatite, barite, bastnäsite, fluorite, monazite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Kangankunde	Malawi	Carbonatite	High	Monazite, bastnäsite	3.7	3.7	3.7	NR	NR	3.3	NR	36,143	336	4.2	0.04
Araxá	Brazil	Carbonatite	High	Monazite, apatite	15	29	2	15	0	374	NR	35,342	565	4.1	0.07
Muluozhai	China	Carbonatite	Low	Bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ruri Complex	Kenya	Carbonatite	Low	Bastnäsite, eudialyte, fluorite, monzite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mrima Hill	Kenya	Carbonatite	High	Apatite, magnetite, barite, fluorite	54	133	17	90	12	1,517	NR	30,585	2,193	3.6	0.27
Chuktukonskoye	Russia	Carbonatite	Medium	Apatite (francolite), barite, cerianite, hematite, ilmenite, monazite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Khanneshin	Afghanistan	Carbonatite	Low	Monazite, synchysite, bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Lugin Gol	Mongolia	Carbonatite	Low	Bastnäsite, fluorite, parisite, pyrite, rutile, synchysite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Kizilcaoren	Turkey	Carbonatite	Low	Bastnäsite, braunite, fluorite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ondurukurme Complex	Namibia	Carbonatite	Low	Monazite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR

NR = not reported

TABLE 7. The 25 Largest (by contained REO) REE Deposits with a Breakdown into Individual REE Concentrations

Project	Country	Principal deposit type	Reliability level	REE mineralogy	TREO + Y (Mt)	Mineral resources (Mt)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)
Bayan Obo	China	Carbonatite	Medium	Bastnäsite, monazite, xenotime	92	1,540	12,628	26,012	2,785	7,943	661	207	310	45	141
Bayun Obo (tailings dam)	China	Tailings	Low	Bastnäsite, monazite, xenotime	83	1,200	NR	NR	NR	NR	NR	NR	NR	NR	NR
Southern seven provinces (Fujian, Guangxi, etc.)	China	Laterite/ soil/clay	Low	Ion-adsorption clay	60	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Olympic Dam	Australia	IOCG	Medium	Granite-rich breccias, florencite, monazite, xenotime	53	9,576	1,705	2,561	NR	NR	NR	NR	NR	NR	NR
Morro dos Seis Lagos	Brazil	Carbonatite	Low	NR	43	2,898	NR	NR	NR	NR	NR	NR	NR	NR	NR
Weishan	China	Carbonatite	Low	Bastnäsite	30	1,856	NR	NR	NR	NR	NR	NR	NR	NR	NR
Tanbreez	Greenland	Alkaline	High	Eudialyte	28	4,300	1,157	2,145	208	780	150	20	163	33	189
Saint-Honoré Comlpex	Canada	Carbonatite	High	Bastnäsite, allanite, apatite, monazite	18	1,058	3,577	6,801	743	2,573	281	60	130	11	36
Tomtor	Russia	Carbonatite	Low	Monzite, pyrochlore	18	150	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chuktukonskoye	Russia	Carbonatite	Medium	Apatite, barite, cerianite, hematite, ilmenite, monazite	17	455	NR	NR	NR	NR	NR	NR	NR	NR	NR
Iron Hill (Powderhorn, Cebolla Creek)	USA	Carbonatite	Low	Monazite, bastnäsite	9.7	2,424	NR	NR	NR	NR	NR	NR	NR	NR	NR
Maboumie	Gabon	Carbonatite	Low	Bastnäsite, monazite, pyrite, pyrochlore, synchysite, xenotime	9.6	380	NR	NR	NR	NR	NR	NR	NR	NR	NR
Palabora (Phalaborwa) Complex	South Africa	Carbonatite	Low	Apatite, pyroxenite	9.6	297	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mau Xe North	Vietnam	Carbonatite	Low	Bastnäsite	7.8	557	NR	NR	NR	NR	NR	NR	NR	NR	NR
Niobec REE zone	Canada	Carbonatite	High	Bastnäsite, allanite, apatite, monazite	7.7	467	3,452	6,756	742	NR	293	60	140	11	40
Dong Pao	Vietnam	Carbonatite	Low	Bastnäsite	7.0	500	NR	NR	NR	NR	NR	NR	NR	NR	NR
Lovozero	Russia	Alkaline	Medium	Loparite, magnetite, eudialyte, rinkite, ancylite, mosandrite	7	612	NR	NR	NR	NR	NR	NR	NR	NR	NR
Kvanefjeld	Greenland	Alkaline	High	Lujavrite	6.6	619	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mrima Hill	Kenya	Carbonatite	High	Apatite, magnetite, barite, fluorite	6.1	159	8,658	14,135	1,428	4,969	697	196	503	62	308
Ashram (Eldor)	Canada	Carbonatite	High	Monazite, bastnäsite, xenotime	6.1	423	3,077	5,746	618	2,208	284	66	157	16	63
Mushagai Khudag (Mushugay-Khuduk)	Mongolia	Carbonatite	Low	Bastnäsite, celestite, fluorite, etc.	5.9	367	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ngualla	Tanzania	Carbonatite	High	Bastnäsite	4.4	195	5,237	9,326	902	3,167	326	69	149	13	32
Strange Lake	Canada	Alkaline	High	Allanite, titanite, pyrochlore, gadolinite	4.4	492	1,034	2,228	248	954	207	9.0	201	40	276
Fen	Norway	Carbonatite	Low	Allanite, monazite, bastnäsite	4.4	486	NR	NR	NR	NR	NR	NR	NR	NR	NR
Thor Lake/ Nechalacho (Basal and Upper zones)	Canada	Alkaline	High	Monazatite, huanghoite, cebaite, qaqarssukite	4.3	312	1,612	4,641	609	2,263	446	53	369	47	216

TABLE 7. (Cont.)

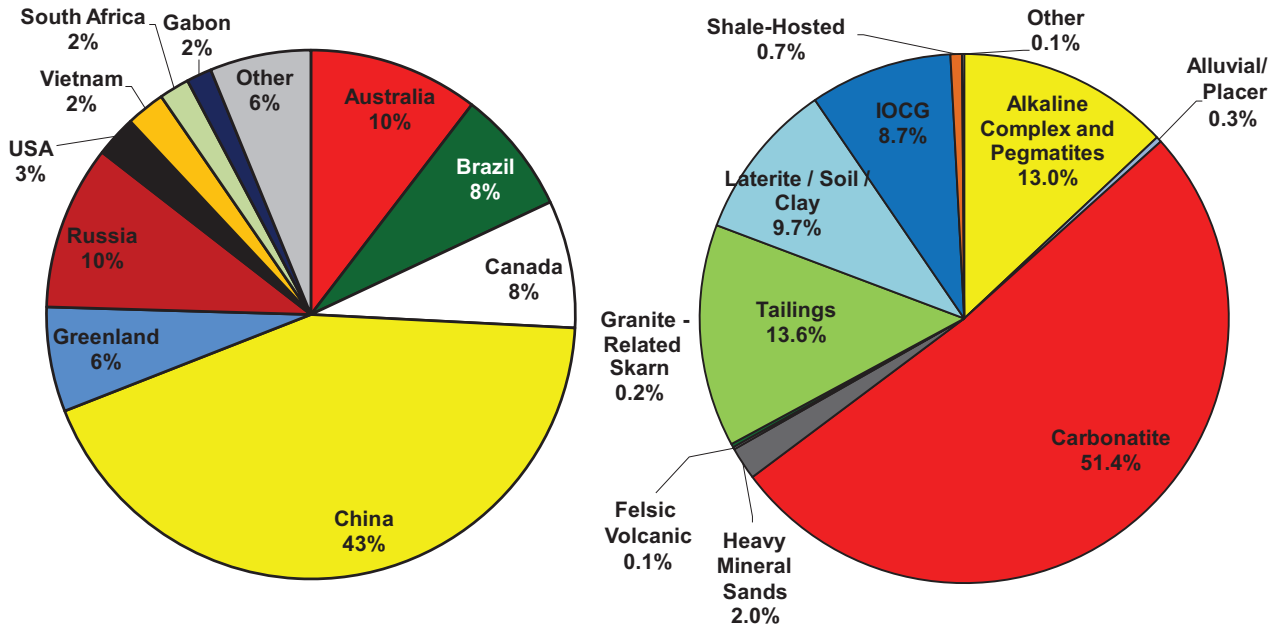| Project	Country	Principal deposit type	Reliability level	REE mineralogy	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Y (ppm)	Sc (ppm)	LREE (ppm)	HREE (ppm)	LREO (%)	HREO +Y (%)	TREO +Y (%)
Bayan Obo	China	Carbonatite	Medium	Bastnäsite, monazite, xenotime	NR	31	NR	91	23	157	NR	50,546	489	5.9	0.06	5.9
Bayun Obo (tailings dam)	China	Tailings	Low	Bastnäsite, monazite, xenotime	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	7.0
Southern seven provinces (Fujian, Guangxi, etc.)	China	Laterite/ soil/clay	Low	Ion-adsorption clay	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Olympic Dam	Australia	IOCG	Medium	Granite-rich breccias, florencite, monazite, xenotime	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.55
Morro dos Seis Lagos	Brazil	Carbonatite	Low	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1.5
Weishan	China	Carbonatite	Low	Bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Tanbreez	Greenland	Alkaline	High	Eudialyte	39	156	20	130	20	1,235	NR	4,622	1,820	0.50	0.15	0.65
Saint-Honoré Conlpex	Canada	Carbonatite	High	Bastnäsite, allanite, apatite, monazite	4.4	7.9	0.88	0.88	0.88	513	NR	14,165	575	1.66	0.07	1.7
Tomtor	Russia	Carbonatite	Low	Monzite, pyrochlore	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	12
Chuktukonskoye	Russia	Carbonatite	Medium	Apatite, barite, cerianite, hematite, ilmenite, monazite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3.8
Iron Hill (Powderhorn, Cebolla Creek)	USA	Carbonatite	Low	Monazite, bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.40
Maboumie	Gabon	Carbonatite	Low	Bastnäsite, monazite, pyrite, pyrochlore, synchysite, xenotime	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	2.5
Palabora (Phalaborwa) Complex	South Africa	Carbonatite	Low	Apatite, pyroxenite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.15
Mau Xe North	Vietnam	Carbonatite	Low	Bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1.4
Niobec REE zone	Canada	Carbonatite	High	Bastnäsite, allanite, apatite, monazite	4.4	8	1.9	NR	0.70	74	28	11,443	140	1.34	0.02	1.7
Dong Pao	Vietnam	Carbonatite	Low	Bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1.4
Lovozero	Russia	Alkaline	Medium	Loparite, magnetite, eudialyte, rinkite, ancylite, mosandrite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1.1
Kvanefjeld	Greenland	Alkaline	High	Lujavrite	NR	NR	NR	NR	NR	680	NR	NR	NR	0.93	0.13	1.1
Mrima Hill	Kenya	Carbonatite	High	Apatite, magnetite, barite, fluorite	54	133	17	90	12	1,517	NR	30,585	2,193	3.58	0.27	3.9
Ashram (Eldor)	Canada	Carbonatite	High	Monazite, bastnäsite, xenotime	9	19	1.8	12	1.8	10	NR	12,157	132	1.36	0.07	1.4
Mushgai Khudag (Mushugay-Khuduk)	Mongolia	Carbonatite	Low	Bastnäsite, celestite, fluorite, etc.	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	1.6
Ngualla	Tanzania	Carbonatite	High	Bastnäsite	4.0	12	NR	4.0	NR	86	NR	19,177	151	2.2	0.02	2.3
Strange Lake	Canada	Alkaline	High	Allanite, titanite, pyrochlore, gadolinite	60	191	28	192	28	1,710	NR	4,881	2,524	0.57	0.31	0.89
Fen	Norway	Carbonatite	Low	Allanite, monazite, bastnäsite	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.90
Thor Lake/ Nechalacho (Basal and Upper zones)	Canada	Alkaline	High	Monazatite, huanghoite, cebaite, qaqarssukite	36	87	12	71	10	836	NR	9,993	1,315	1.2	0.16	1.4

NR = not reported

Fig. 5. Percentage of global REO resources split by country (left) and by principal deposit type (right). The "other" category of the global REO resources split by country summarized REO resource data from all the other countries (e.g., Afghanistan, Argentina, Finland, Peru, Sweden, etc.) covered in our dataset. The details of all countries' REO resources are presented in Table 5. The "other" category of the global REO resources by principal deposit types includes REO resources from granites and granitic pegmatites, sedimentary undifferentiated, carbonatite-related skarn, and hydrothermal undifferentiated types of deposits.

the HREE have resources that are an average of three orders of magnitude lower than the other REE (e.g., 0.34 Mt Tb, 0.26 Mt Ho, and 0.16 Mt Lu). This is reflected by the grades within our database, where Ce, La, and Nd have average grades of 3,379, 1,853, and 823 ppm, respectively, compared

to the average grades of 464, 52, and 33 ppm for Y, Dy, and Er, respectively.

The average distribution of the individual REE within individual deposit types is summarized in Table 9. These data indicate that IOCG, carbonatite, and hydrothermal projects are
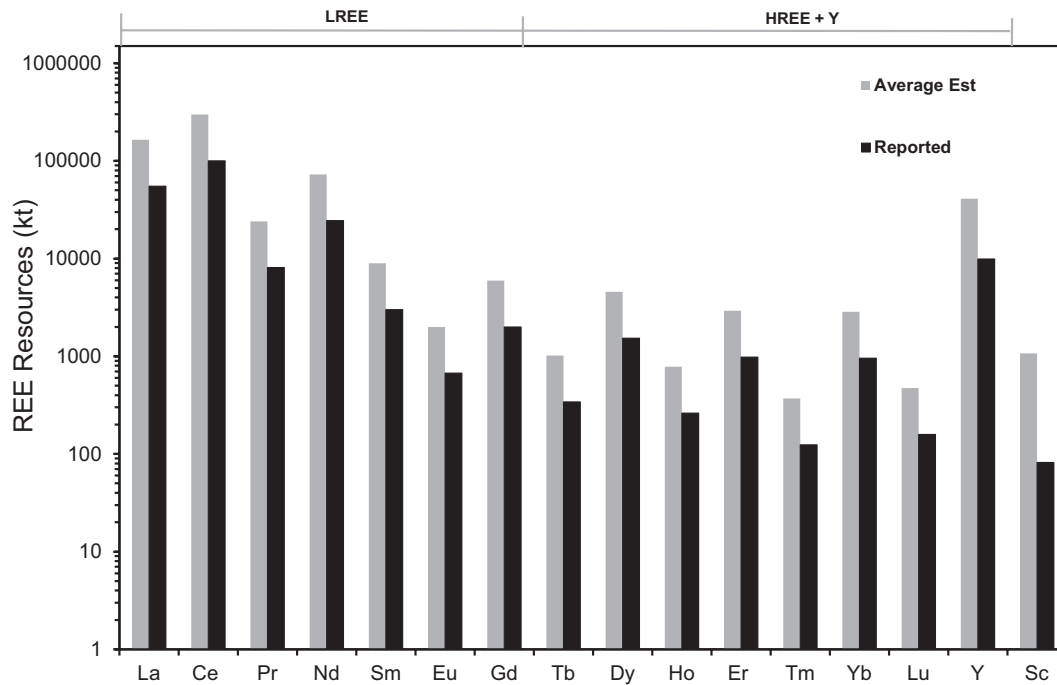
Fig. 6. Summary of individual REE resources with reported data and average estimates. Average estimates are calculated based on weighted average grade of each individual REE + Y.

TABLE 8. Summary of Mineral Resources and REE Grades by Deposit Type, Including Mean and Standard Deviation Values

Deposit type	Mineral resources (Mt)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)
Alkaline complex and pegmatites (51)	13,621	1,002 ± 6,799 (19)	1,957 ± 14,019 (19)	213 ± 1,883 (13)	795 ± 6,867 (14)	154 ± 1,069 (14)	21 ± 35 (14)	157 ± 736 (14)	31 ± 79 (14)
Alluvial/placer (7)	1,099	94 ± 207 (5)	187 ± 464 (5)	19 ± 58 (5)	68 ± 231 (5)	13 ± 55 (5)	1.5 ± 0.4 (4)	10 ± 62 (5)	2 ± 11 (5)
Carbonatite (68)	21,993	7,093 ± 5,918 (21)	13,886 ± 10,012 (21)	1,490 ± 980 (21)	4,286 ± 3,275 (21)	443 ± 427 (21)	120 ± 102 (20)	217 ± 230 (20)	30 ± 27 (20)
Felsic volcanic (3)	1,084	41 ± 889	125 ± 1,870	15 ± 210	48 ± 765	15 ± 130	0.4 ± 6	15 ± 96	5 ± 14
Heavy mineral sands (100)	27,747	2.3 (1)	4.9 (1)	0.6 (1)	2.0 (1)	0.3 (1)	0.09 (1)	0.2 (1)	0.03 (1)
Granite-related skarn (7)	60	3,707 ± 1,813 (5)	9,450 ± 4,632 (5)	1,152 ± 565 (5)	4,018 ± 1,931 (5)	465 ± 171 (5)	80 ± 28 (5)	238 ± 175 (5)	25 ± 46 (5)
IOCG (4)	9,764	1,675 ± 1,115 (2)	2,516 ± 1,654 (2)	21 (1)	69 (1)	10 (1)	4 (1)	9 (1)	N/A
Laterite/soil/clay (2)	435 (1)	145 (1)	265 (1)	30 (1)	99 (1)	18 (1)	2 (1)	15 (1)	2 (1)
Shale hosted (5)	6,449	41 ± 1 (2)	72 ± 2 (2)	9 (2)	34 ± 0.4 (2)	7 ± 0.1 (2)	1 (2)	6 (2)	1 (2)
Tailings (7)	1,512	1,289 ± 7,846 (4)	2,426 ± 9,235 (4)	287 ± 2,097 (4)	1,215 ± 7,445 (4)	230 ± 1,165 (4)	30 ± 39 (4)	273 ± 809 (4)	142 ±62 (4)
Average REE grade (ppm)		1,853 ± 4,712 (63)	3,379 ± 10,798 (63)	271 ± 1,328 (57)	823 ± 4,712 (56)	101 ± 696 (57)	23 ± 81 (55)	67 ± 474 (56)	11 ± 56 (55)
Reported REE resources (kt)		55,060	100,391	8,079	24,450	3,006	671	1,999	341
Average estimate (kt)		163,959	298,983	23,979	72,821	8,937	2,035	5,928	973

Deposit type	Mineral resources (Mt)	Dy (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Y (ppm)	Sc (ppm)
Alkaline complex and pegmatites (51)	13,621	170 ± 362 (14)	35 ± 57 (13)	132 ± 120 (14)	17 ± 13 (12)	114 ± 66 (14)	17 ± 9 (12)	1,051 ± 1,544 (27)	11 ± 0.46 (2)
Alluvial/placer (7)	1,099	8 ± 65 (5)	2 ± 15 (5)	4 ± 39 (5)	0.6 ± 6 (4)	4 ± 35 (5)	0.5 ± 4 (4)	42 ± 362 (5)	5 (1)
Carbonatite (68)	21,993	89 ± 126 (20)	9 ± 126 (18)	23 ± 44 (19)	2 ± 5 (15)	38 ± 30 (18)	9 ± 6 (13)	274 ± 489 (21)	29 ± 11 (2)
Felsic volcanic (3)	1,084	38 ± 83	37 ± 1 (2)	38 ± 59	8 ± 6	59 ± 33	9 ± 4	253 ± 426	N/A
Heavy mineral sands (100)	27,747	0.06 (1)	0.01 (1)	0.02 (1)	N/A	0.01 (1)	0.01 (1)	0.2 (1)	N/A
Granite-related skarn (7)	60	128 ± 362 (5)	22 ± 88 (5)	59 ± 272 (5)	8 ± 40 (5)	46 ± 240 (5)	7 ± 33 (5)	634 ± 2,255 (5)	N/A
IOCG (4)	9,764	7 (1)	N/A	4 (1)	N/A	N/A	N/A	41 (1)	N/A
Laterite/soil/clay (2)	435 (1)	13 (1)	3 (1)	8 (1)	1 (1)	7 (1)	1 (1)	75 (1)	N/A
Shale hosted (5)	6,449	5 ± 0.2 (2)	1 (2)	3 (2)	41 ± 1 (2)	3 (2)	0.5 ± 0.1 (2)	32 ± 1 (2)	12 ± 2 (2)
Tailings (7)	1,512	150 ± 380 (4)	46 ± 21 (4)	133 ± 84 (4)	39 ± 17 (4)	137 ± 246 (4)	46 ± 23 (4)	1,304 ± 1,021 (4)	194 (1)
Average REE grade (ppm)		52 ± 282 (56)	9 ± 51 (52)	33 ± 142 (55)	4 ± 21 (46)	32 ± 130 (52)	5 ± 18 (45)	464 ± 1,397 (71)	13 ± 63 (8)
Reported REE resources (kt)		1,532	263	983	124	959	158	9,902	82
Average estimate (kt)		4,601	796	2,920	354	2,831	442	41,056	1,150

Notes: Parentheses indicate number of data points used to calculate each value; "average estimates" are calculated based on a weighted average grade for individual elements; N/A = data not available

TABLE 9. Average Proportional Distributions of the REE Split by Deposit Type

Deposit type	La (wt %)	Ce (wt %)	Pr (wt %)	Nd (wt %)	Sm (wt %)	Eu (wt %)	Gd (wt %)	Tb (wt %)	Dy (wt %)	Ho (wt %)	Er (wt %)	Tm (wt %)	Yb (wt %)	Lu (wt %)	Y (wt %)	No.
Alkaline	17	33	3.6	14	2.6	0.36	2.7	0.53	2.9	0.60	2.3	0.29	1.9	0.29	18	27
Alluvial/placer	21	41	4.2	15	2.9	0.33	2.2	0.44	1.8	0.44	0.88	0.13	0.88	0.11	9.2	5
Carbonatite	25	50	5.3	15	1.6	0.43	0.77	0.11	0.32	0.032	0.082	0.0071	0.14	0.032	0.98	21
Felsic volcanic	5.8	18	2.1	6.8	2.1	0.057	2.1	0.71	5.4	5.24	5.4	1.1	8.4	1.3	36	3
Granite-related skarn	18	47	5.7	20.1	2.3	0.40	1.2	0.1	0.6	0.11	0.29	0.040	0.23	0.035	3.2	5
Heavy mineral sand	21	46	5.6	19	2.8	0.84	1.9	0.28	0.56	0.093	0.19	NR	0.093	0.093	1.9	1
IOCG	38	58	0.48	1.6	0.23	0.092	0.21	NR	0.1607	NR	0.092	NR	NR	NR	0.941	2
Laterite/soil/clay	21	39	4.4	14	2.6	0.29	2.2	0.29	1.9	0.44	1.2	NR	1.0	0.15	11	1
Shale hosted	16	28	3.5	13	2.7	0.39	2.3	0.39	1.9	0.39	1.2	16	1.2	0.19	12	2
Tailings	17	31	3.7	16	3.0	0.39	3.5	1.8	1.9	0.59	1.7	0.50	1.8	0.59	17	4

No. = number of deposits with reported individual REE concentrations; NR = not reported

unsurprisingly LREE dominated, containing >90% LREE or Ce and La where specified for individual deposits. Felsic volcanic, granite-related, and alkaline deposits usually have REO resources that contain more HREE, although, again, a lack of available individual element data for all projects has limited our capacity to assess the full picture of REE distribution within all potential REE deposits. However, even given this, there are significant differences in the distribution of the individual REE (especially the HREE) in the resources evident in Table 9, a fact that has implications for targeting of deposit types that preferentially contain the more valuable HREE.

Despite the significance of individual REE concentrations, most mining companies rarely provide REE resource estimates that contain these crucial data, with only 71 of the 260 deposits within our database reporting individual REE concentration data, and a further 10 deposits that only report Y concentrations rather than individual concentrations for all of the REE. This situation is also exemplified by the data shown in Tables 6 and 7, where individual REE concentrations are not reported for some of the most significant REE projects in our database (e.g., the Tomtor project in Russia, the Pea Ridge deposit in the United States, and the Morro dos Seis Lagos deposit in Brazil). This insufficient reporting means that our database contains significant variations in average REE concentrations (especially the HREE) for different types of REE mineral deposits, which could be attributed to the natural variability of these deposits, the changing geologic settings of these REE projects, a lack of sufficient data and associated reporting to provide a comprehensive picture for each type of deposit, or some combination of all of these factors.

Average individual concentrations were calculated for individual deposit types to provide an estimate of the distribution of the individual REE within individual projects; these data were then used to estimate individual REE resources within the 196 of the 260 deposits in our dataset that do not have formally reported individual REE concentrations. This approach involves assessing the individual REE resources within a given type of REE deposit using the compiled total mineral resources from all deposits in the same deposit-type category combined with corresponding weighted average REE fractions calculated for those deposits that reported individual REE concentrations within this deposit class. This assessment confirms that significant differences are present between LREE and HREE resources (as summarized in Fig. 6 and Table 8), and our estimates indicate that Ce is the most abundant of all of the REE within our database (~299 Mt contained elemental Ce), followed by La (~164 Mt), with Y unsurprisingly dominating the HREE budget of these deposits (~41 Mt contained elemental Y). Although, chemically, Y does not belong to the lanthanide group of elements, it constitutes more than 56% of the entire HREE metal resource, further indicating the natural scarcity of critical HREE like Dy, Yb, and Lu. Despite the insufficient reported data and uncertainties involved in these scenarios, the three orders of magnitude difference between LREE and HREE resources again indicates that global REE resources contain far lower amounts of the HREE than the LREE.

The complex substitution-dominated mineralogy of the REE and the relatively limited scale of global REE mining means that REE deposits are associated with a wide range

of critical co- and by-product elements (e.g., Zr, Nb, Li, Hf, Ta, etc.). However, the relationship between these co- and by-products and the differing types of REE deposits has not as yet been fully assessed. As summarized in Table 5 and the supplementary information, our compiled dataset provides an initial step in quantitatively assessing these relationships. A number of alkaline complex and pegmatite REE deposits contain reported economic concentrations of Zr (16 out of 48) and Nb (15 out of 48), suggesting (as expected) a link between these deposits and Zr and Nb enrichment. The carbonatite deposits that dominate global REE resources are variably enriched in a wide variety of by- and co-product elements, such as Nb, Zr, Fe, Sr, and F, whereas shale-hosted REE deposits contain the most diverse by-/co-products, including Zn, Cu, Co, V, Ni, Mo, Sc, Li, Al, and pure silica, among others. Th and U are the two most common radioactive impurities reported within the REE deposits in our database (118 deposits report Th grades and 40 deposits provide U concentrations), with average concentrations of 81 ppm Th and 127 ppm U. It should be emphasized that our study is primarily based on reported mineral resources that provide information on geologic probability rather than economic feasibility for extraction. However, this, in turn, also indicates that a significant amount of coexisting and economically important elements may be present within these REE deposits. These elements either are not present at sufficient concentrations, have not undergone sufficient metallurgical testing to be reported as yet, or may not be extractable as a result of processing difficulties or prohibitive costs to be classified as part of individual reported mineral resources and, hence, have not been included in our dataset.

Discussion: Assessing Rare Earth Element Resources

Shifting from one dominant supplier (i.e., China) to a more diverse global REO supply chain is crucial for ensuring long-term REE resource security and meeting growing global demands for the REE. Our database indicates that global known REE resources are some 619.5 Mt TREO + Y hosted by 267 deposits, with the 260 deposits that have known grades and tonnages having an average concentration of 0.63% TREO + Y (Table 4), with 111, 199, and 310 Mt contained TREO + Y in high-, medium-, and low-reliability category deposits, respectively. Current TREO + Y resources are dominated by the LREE, with an average LREO (La-Gd) to HREO (Tb-Lu + Y) ratio of 13:1. Although China hosts significant TREO + Y resources (~268 Mt) and the largest operating REE project (i.e., Bayan Obo; Table 5), some 57% of the global TREO + Y resources within our database are hosted by deposits outside of China (Fig. 5). These deposits are located in a number of different countries, including Australia (e.g., Mt. Weld, Nolans Bore, etc.), Canada (Niobec, Nechalacho, etc.), Brazil (Araxá, etc.), Russia (Tomtor, Chuktukonskoye, etc.), and Greenland (Tanbreez, Kvanefjeld, etc.), all of which host numerous potential REE deposits containing abundant REO resources. From a geographic perspective, the transitioning of these potential deposits into production means that they could become significant suppliers within the global REE market and therefore mitigate any potential supply risks associated with the dependence on a single supplier. However, China's monopoly within the global REE industry is not only based upon the largest REO resource endowment but also benefits from its dominant position in REE processing, specialized human capital, particular technical expertise, alloying, and downstream manufacturing (USDOE, 2010). In order to cope with these challenges, a significant amount of time and resources will be required to establish a competitive and sustainable REE supply chain outside China; hence, any change toward a more diverse global REE market must necessarily be gradual.

Various estimates of global REE resources have been published by different geological, scientific, and governmental organizations (Table 3), with the majority of these estimates focused on REE ore reserves. In comparison, our approach is based on reported project-specific mineral resources that are categorized by the reliability of the available data (i.e., high, medium, and low). This study inevitably involves a variety of uncertainties, as illustrated by the large number of medium- (126 out of 267 projects) and low- (76 out of 267 projects) reliability resources in our dataset. This is exemplified by the Bayan Obo deposit, which, despite the fact that it has been the largest operating REE mine in the world since the 1960s, has an uncertain resource, with many reports including highly variable mineral resource estimates for the deposit, such as one from the Chinese Society of Rare Earths (CSRE, 2002), which reported that Bayan Obo contained 43.5 Mt TREO + Y "industrial reserves" plus 106 Mt "measured reserves," compared to one from the Ministry of Land and Resources of the People's Republic of China (MoLRPRC, 2012), which published a reserve estimate for Bayan Obo of 91.59 Mt of contained TREO + Y in addition to other critical minerals such as Nb (2.16 Mt contained Nb_2O_5). This just highlights some of the uncertainties involved in predicting the security of future supplies of the REE and other critical metals.

Similar uncertainties also surround the REE resources within Australia's Olympic Dam deposit. According to Geoscience Australia, Olympic Dam contained about 53 Mt TREO + Y in December 2011 (Hoatson et al., 2011), which, when combined with the published 2011 total mineral resource of 9,292 Mt (BHP Billiton Ltd. [BHPB], 2011a), suggests an approximate grade of 0.55% TREO + Y for the deposit. The deposit is also known to contain about 2,000 ppm La and 3,000 ppm Ce (Oreskes and Einaudi, 1990), suggesting a combined La-Ce oxide grade of 0.59% (using an X_2O_3 formula). Combining these concentrations with an assumption that all of the other REE within the deposit form some 10% of the total REE budget within Olympic Dam (i.e., 90% La and Ce, as the deposit is known to be LREE dominated; Oreskes and Einaudi, 1990; Reeves et al., 1990) and a decline in the REO grade of the deposit by one-third (in accordance with declining Cu grades in reported mineral resources for Olympic Dam) suggests that Olympic Dam has an approximate grade of 0.48% TREO + Y, consistent with previous research (Oreskes and Einaudi, 1990; Reeves et al., 1990). However, despite the fact that Olympic Dam contains a significant amount of the REE, BHP Billiton has no plans to attempt to convert this potential resource into production (BHPB, 2011b), meaning that other information on this project, such as mineralogy and individual REE concentrations, are not included within annual mineral resource reporting for the Olympic Dam deposit (e.g., BHPB, 2012).

In general, the majority of mineral exploration or mining project resources focus on a single deposit (e.g., Olympic Dam, Niobec, etc.), although some resources cover a group of individual orebodies or a mining camp (e.g., Norra Kärr, Saint-Honoré carbonatite complex). Increasing global demand for the REE has stimulated exploration and the examination of extraction from all possible types of REE mineralization. Despite this, numerous other types of potentially major REE resources either have not been systematically assessed or are not covered in our dataset, including ion-absorbed clay deposits outside China (Moldoveanu and Papangelakis, 2012), deep-sea Fe-Mn nodules (Kato et al., 2011; Parhi et al., 2013; Bau et al., 2014), and river sediments (Yang et al., 2002), primarily due to the current lack of available resource, grade, and tonnage data for these prospects. The existing estimates of REE abundances within these more esoteric deposit types are mainly geologic resources that do not have demonstrable potential for economic mining, cannot be currently considered a formal mineral resource, and are therefore excluded from our dataset.

From a beneficiation and processing perspective, REE production does not simply involve the concentration of ore minerals such as sulfides or native metals (as is the case for many base and precious metal deposits) but instead requires the selective separation of each individual REE from the hosting minerals and subsequent production of a single element concentrate or product (e.g., Weng et al., 2013). Consequently, REE deposits require complex and, in most cases, site-specific processing and refining (e.g., milling, flotation, electromagnetic separation, gravity concentration, hydrometallurgy, solvent extraction, etc.) to produce desired and saleable products (e.g., high-purity REE metals, REO, mixed or "misch" metals or oxides). Variations in deposit type, mining configuration, by-/co-product makeup, human capital, social, economic, and environmental constraints will necessarily lead to different beneficiation and processing facility designs for specific REE projects. This complexity is exemplified by the different REE processing routes used by two well-known bastnäsite-based carbonatite REE mines, namely Bayan Obo in China, where a sulfuric acid baking approach is used for processing of REE ore, and Mountain Pass in California, United States, where a primarily alkali based process flow sheet is used (Fig. 7). Our study indicates that the abundant known REE mineral resources are hosted by a variety of different types of mineral deposits, each of which has a diverse range of mineralogy (e.g., apatite, eudialyte, etc.) and all of which may potentially contribute to meeting current and future global demand for the REE. However, capitalizing on these resources requires new beneficiation and processing facilities to be developed for individual REE deposits, all of which will need to be researched, implemented, and responsibly maintained, requiring a significant investment in capital (both tangible and intangible) and in scientific and technological research from industry, government, and local communities.

There are notable differences between the concentrations of individual REE within different types of REE deposits (Table 8), with current global REE supply dominated by production from a limited number of LREE (La, Ce, Nd, and Pr)-enriched but HREE (Dy, Tb, Er, etc.)-poor carbonatite deposits (e.g., Bayan Obo in China, Mountain Pass in the United States, and Mount Weld in Australia). However, the fact that economic growth is driving the domestic growth of REO consumption in China, combined with an increase in global demand driven by the development and application of green technology like hybrid cars, fuel cells, and wind turbines, all of which require HREE in addition to the more abundant LREE (USDOE, 2010; Humphries, 2013), means that future REE supply almost certainly needs to shift from a few bastnäsite-based carbonatite mines toward a more diversified range of production from a range of differing types of REE projects.

The increasing use of the REE also simultaneously alters the definition of "end products" within the rare earth supply chain. Exponential growth in the demand for more refined products either as high-purity metals (Dy, Nd, Tb, etc.) or as mischmetals (e.g., SmCo, NdFeB, etc.) for use in modern technology cannot be simply met by an overall increase in REO production capacity. This is exemplified by the projected increase in REE-dependent green technology that is required to stabilize atmospheric CO_2 at 450 ppm, a development that would require an increase in annual Dy production of some 2,600% between the present day and 2035 (Alonso et al., 2012). The coexisting nature of the REE and the relatively low abundance of the HREE mean that such a dramatic increase in one particular element may inevitably lead to the oversupply of the other REE as well as potentially increased production of co- and by-products such as Cu, Fe, and Ti, which may lead to the production of elements other than Dy far exceeding demand, but also potentially not meeting the demand for Dy, given the dramatic predicted increase in production that Alonso et al. (2012) indicates may be required. An increase in overall REE production would also lead to a significant increase in the production of impurities, tailings, and hazardous residues (e.g., Th and U) that are beyond current industrial processing and waste treatment capacities. Our research indicates that the current average LREO to HREO ratio of 13:1 within known global REE resources presents both a challenge and a limitation to future REE production in that future REE mining may result in an excess of LREE production while also not meeting the demands for certain HREE, such as Dy. This means that the development of individual REE-specific mining, beneficiation, and processing methodologies that target deposits with suitable mineralogies will be needed to improve the processing efficiency and production capacity of specific REE-dependent end products.

In order to model future trends in REE production and resource availability, we have also undertaken conceptual modeling of the future availabilities of Dy, Tb, Nd, Ce, and La (covering both the HREE and the LREE) up to the year 2100 using the database presented in this paper. Although this modeling does not explicitly include the complexity of all economic factors, this approach simply projects historic patterns of continually growing demand for the REE forward to compare the derived cumulative estimates with the currently known global REE resources documented here. Historical data published by the USGS (1994–2011, 1997–2015) indicates a historic annual growth in REE production of 5.6% over the past 50 years, with an annual growth rate before 1970 of approximately 3%. Moss et al. (2013b) also predicted that growth in REE demand could reach 6.64% by 2030 as
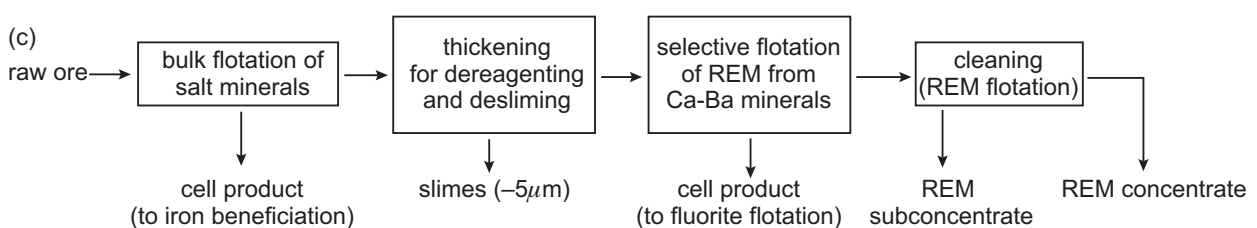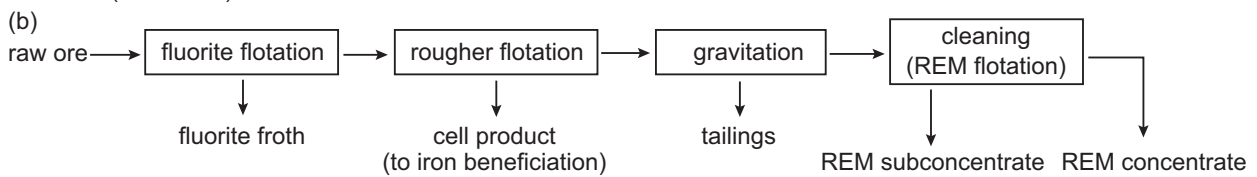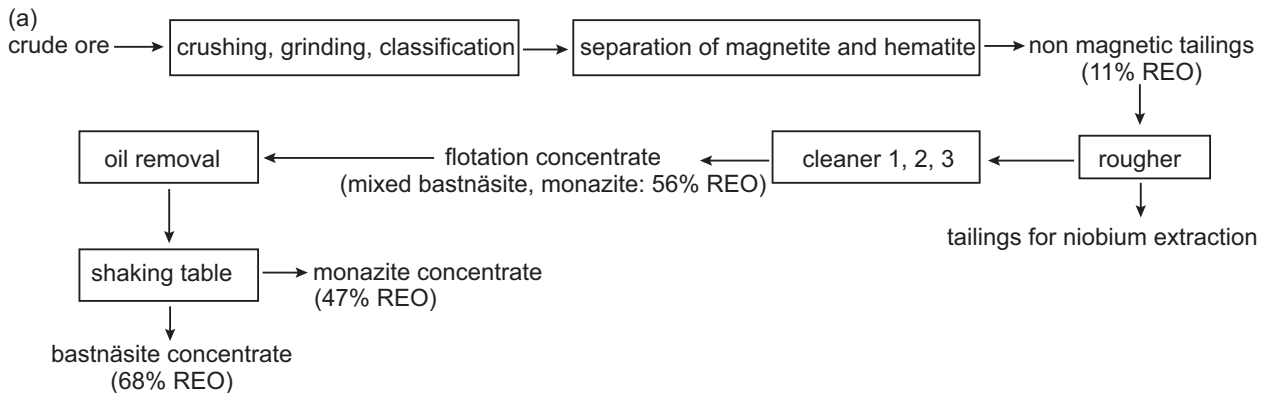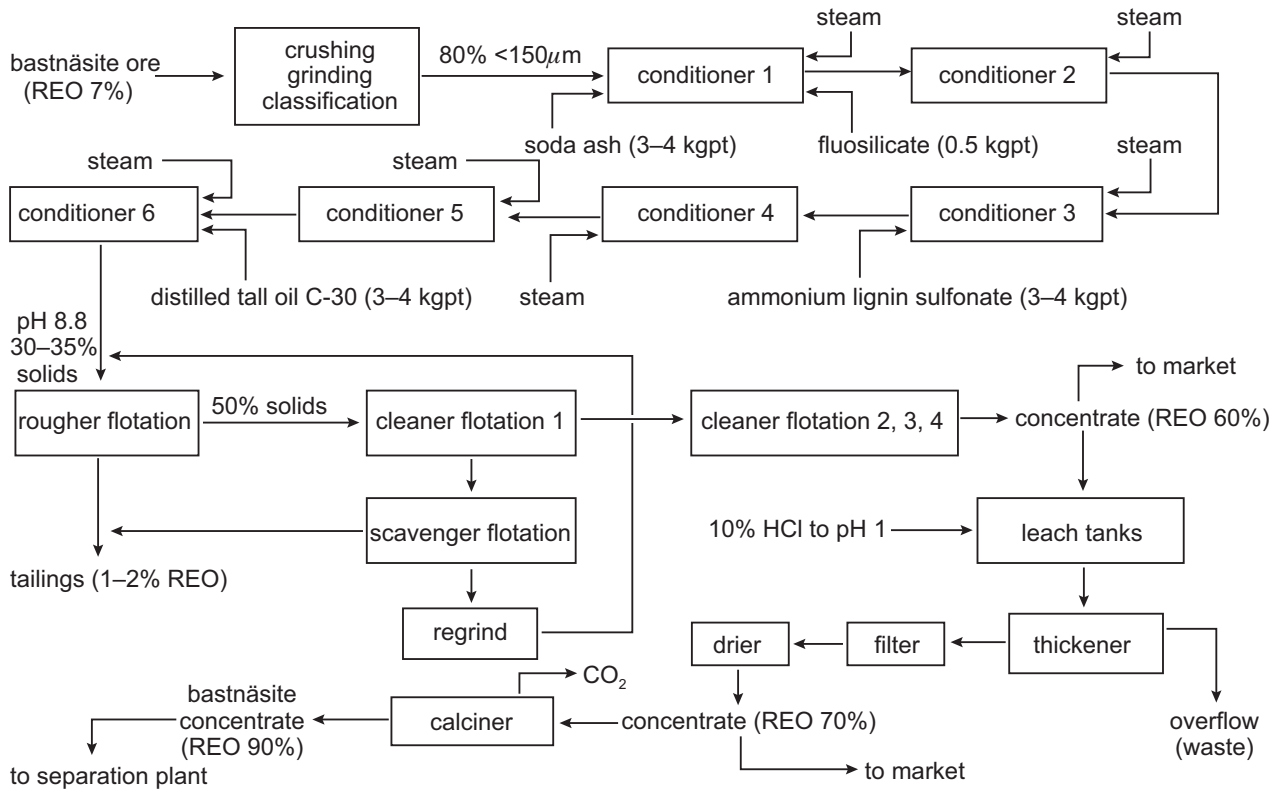
bastnäsite ore (REO 7%) → crushing grinding classification → 80% <150μm → conditioner 1

steam

steam

soda ash (3–4 kgpt)

fluosilicate (0.5 kgpt)

conditioner 2

steam

steam

conditioner 6 ← steam ← conditioner 5 ← steam ← conditioner 4 ← conditioner 3

distilled tall oil C-30 (3–4 kgpt)   steam   ammonium lignin sulfonate (3–4 kgpt)

pH 8.8 30–35% solids

rougher flotation → 50% solids → cleaner flotation 1 → cleaner flotation 2, 3, 4 → concentrate (REO 60%) → to market

tailings (1–2% REO)

scavenger flotation

10% HCl to pH 1 → leach tanks

regrind

drier ← filter ← thickener

CO₂

calciner ← concentrate (REO 70%)

overflow (waste)

bastnäsite concentrate (REO 90%)

to separation plant

to market

(a) crude ore → crushing, grinding, classification → separation of magnetite and hematite → non magnetic tailings (11% REO)

oil removal ← flotation concentrate (mixed bastnäsite, monazite: 56% REO) ← cleaner 1, 2, 3 ← rougher

tailings for niobium extraction

shaking table → monazite concentrate (47% REO)

bastnäsite concentrate (68% REO)

(b) raw ore → fluorite flotation → rougher flotation → gravitation → cleaning (REM flotation)

fluorite froth   cell product (to iron beneficiation)   tailings   REM subconcentrate   REM concentrate

(c) raw ore → bulk flotation of salt minerals → thickening for dereagenting and desliming → selective flotation of REM from Ca-Ba minerals → cleaning (REM flotation)

cell product (to iron beneficiation)   slimes (−5μm)   cell product (to fluorite flotation)   REM subconcentrate   REM concentrate

FIG. 7. Bastnäsite processing routes for Mountain Pass (above) and Bayan Obo (below; adapted from Gupta and Krishnamurthy, 2005).

result of the increased production of new technologies requiring greater amounts of various REE (especially the HREE). The two primary scenarios used during this study are (1) a conservative 3% annual growth rate for REE demand (based on historical growth rates before 1970) and (2) an optimistic 5% annual growth rate for REE demand (assuming greater demand for new technologies). Although some studies predict a considerably higher growth rate for specific elements (e.g., Alonso et al., 2012, predicted 9–14% annual growth for Dy production up to 2035 to meet the demand of renewable energy applications), we have adopted a more conservative approach to address longer-term growth, primarily as the historical growth of mineral production is a more reasonable basis for these estimates.

Both 3% and 5% growth scenarios are summarized in Table 10. Dy is the least abundant of the REE considered in our modeling, but even this element still has 37% or 1.7 Mt of contained Dy in mineral resources left under the most rapid growth (5% annual growth rate) scenario, whereas Ce, the most abundant REE considered in our modeling, has 80% or 219 Mt of resources left in 2100 after 88 years of production within our rapid growth scenario. Modeling of the demand for TREO + Y indicates that approximately 74% of current resources will be available by 2100, even under optimistic 5% growth rates. In other words, current global REE mineral resources are sufficient to meet the demands for at least the next 90 years, even including significant growth in the demand for these elements, suggesting that future REE supply will not be constrained by geologic resource scarcity but by other crucial factors, such as economics, mining conditions, processing characteristics, site-specific environmental issues (especially land use, radiation, water, and mine waste management), social constraints (e.g., public health, biodiversity, government policy, and political issues), energy sources and costs, and so on. The fact that this assessment is solely based on geologic resource availability and REO production trends clearly indicates that many other factors need to be considered in more detailed modeling of future global REE supply and demand, such as economic constraints, human capital, geopolitical considerations, variations in demand, changing end products, etc., all of which need be taken into account during further detailed research in this area.

The economic feasibility of a typical mining project (e.g., Cu, Fe) is often determined through the analysis of orebody sizes, ore grades, and the primary mineralogy of the deposit in question. However, the complexity of REE mineralogy, processing, refining methodologies, and differing demands means that the 16 individual REE (excluding Pm) could be produced either as pure metals at various grades, as mischmetals, or as

REO concentrates. In addition, the presence of numerous valuable and potential by-/co-products (e.g., Fe, Nb, Zr, Ti, Th, U, etc.) within REE deposits means that the in situ values of individual REE mineral resources and principal by-/co-products are most likely to be the determining factors in terms of the targeting of individual commodities to be extracted and processed, which, in turn, will determine whether a given REE deposit proceeds into production. As summarized in Table 11, the presence of certain elements (e.g., Sc, Hf, etc.) at seemingly negligible concentrations could substantially change the potential economic value of an REE deposit. For example, despite its relatively low abundances, the presence of potentially extractable Sc (admittedly calculated at a pure Sc price) significantly affects the potential value of some REE projects (e.g., Buckton, Niobec). However, from a production perspective, Sc prices are highly speculative, depending on end usage, and the global demand for Sc is exceptionally small compared to the other REE (widely considered to be a demand of less than 10 t Sc per year; USGS, 1997–2015); hence, it is hard to translate this economic interest into consequences for a real REE project. Given the limited participants involved in global REE trading and the highly sensitive nature of commercial transactions, the REE are not traded through a public exchange (e.g., the London Metals Exchange) and, hence, they do not have formal trading prices. Other factors like sample size, purity, and varying end uses also lead to highly volatile prices for these critical metals. This is exemplified by a comparison of 2013 USGS data (1997–2015) for Sc, indicating a value of US$175,000/kg Sc metal (unspecified purity) and US$6,000/kg for 99.9995% Sc oxide, with data from HEFA Rare Earth Inc. (HEFA, 2014), which listed a price of US$15,500/kg for Sc metal with a 99.9% purity, showing some of the uncertainties related to the economic assessment of REE projects. In addition, it should also be noted that new technological applications, such as uses in wind turbines, hybrid batteries, fuel cells, and permanent magnets, among others, could also increase the demand for a given metal, therefore substantially stimulating the market price of a given REE. The fact that REE processing is often deposit or even mineral specific, as discussed above, also means that improving the efficiency of processing and refining of high-value but low-grade REE deposits as well as more efficient beneficiation and processing of coexisting REE are undoubtedly going to be a challenge for the future of global REE mining.

Tailings from previous mining operations are also a potentially significant source of REE (as shown in Fig. 5). For instance, Bayan Obo has operated as an iron ore mine since the early 1930s, with the first REE refinery plant at the site established in 1963 (CSRE, 2002), meaning that approximately 83.4

TABLE 10. Modeling of REE/REO Cumulative Production for 2012–2100 at 3% and 5% Annual Growth Rates

	Unit	Dy	Tb	Nd	Ce	La	TREO + Y
2012 global production	t	1,917	278	17,147	35,858	26,433	110,000
Cumulative demand 3% annual growth rate	Mt	0.82	0.13	7.8	16	12	45
Cumulative demand 5% annual growth rate	Mt	2.9	0.47	28	60	44	159
Estimated mineral resource (our average data)	Mt	4.6	1.0	73	299	164	619
Remaining mineral resource by 2100 (5% scenario)	%	37	54	61	80	73	74

Notes: Production data used for this modeling are from USDOE (2010) and USGS (1994–2011, 1997–2015)

TABLE 11. The 25 Most Valuable REE Deposits in Our Database Ranked by Largest Combined Value (US$billion), Including Selected Potential By-/Co-products and Proportional Values (%)

Project	Country	Mineral resource (Mt)	Value (US$ billion)	Average ore value ($/t)	LREE value (%)	HREE + Y value (%)	TREE + Y value (%)	Co-product value Sc (%)	Th (%)	U (%)	Zr (%)	Nb (%)	Hf (%)	Ta (%)	Ga (%)	Other
Bayan Obo	China	1,540	3,487	2,265	85	11	95	NR	1	NR	NR	2	NR	NR	NR	Fe (ore) (2%)
Tanbreez	Greenland	4,300	2,527	588	33	67	100	NR	NR	NR	NR	NR	NR	NR	NR	NR
Olympic Dam	Australia	9,576	1,284	134	38	NR	38	NR	NR	10	NR	NR	NR	NR	NR	Au (10%), Ag (0.8%), Cu (40%)
Strange Lake	Canada	492	1,156	2,348	9	24	32	NR	0.6	0.1	55	2	10	NR	NR	NR
Buckton	Canada	4,712	1,028	218	4	5	8	85	0.3	0.3	NR	NR	NR	NR	NR	V_2O_5 (4%), Li (1%), Ni (0.6%), Mo (0.3%)
Thor Lake/Nechalacho (Basal and Upper)	Canada	312	904	2,900	17	12	29	NR	0.2	NR	63	4	NR	2	2	NR
Saint-Honoré Complex	Canada	1,058	683	645	88	12	100	NR	NR	NR	NR	NR	NR	NR	NR	NR
Niobec (REE zone)	Canada	467	408	875	39	5	45	49	3	NR	NR	3.7	NR	NR	NR	Sr (0.01%)
Ghurayyah	Saudi Arabia	385	364	910	0.3	11	11	NR	3	0.8	69	11	NR	5	NR	Sn (0.8%)
Mrima Hill	Kenya	159	323	2,027	62	24	86	NR	1	0.08	NR	12	NR	NR	NR	NR
Ashram (Eldor)	Canada	423	246	582	87	13	100	NR	NR	NR	NR	NR	NR	NR	NR	NR
Motzfeldt (Aries)	Greenland	340	214	629	18	14	32	NR	NR	NR	51	13	NR	3.8	NR	NR
Ngualla	Tanzania	195	147	753	94	6	100	NR	NR	NR	NR	NR	NR	NR	NR	NR
Montviel	Canada	251	139	555	83	16	100	NR	NR	NR	NR	0.5	NR	NR	NR	NR
Canakli 2	Turkey	414	130	263	8	4	12	65	0.7	0.2	11	1	NR	NR	4	Fe (ore) (2%), Ti (5%)
Buckton South	Canada	497	127	256	3	4	7	86	0.2	0.2	NR	NR	NR	NR	NR	V_2O_5 (4%), Li (1%), Ni (0.5%), Mo (0.3%), Co (0.2%), Zn (0.2%), Cu (0.1%)
Dubbo Zirconia (Toongi)	Australia	73	126	1,720	NR	5	5	NR	NR	NR	80	NR	12	3	NR	NR
Norra Kärr	Sweden	58	114	1,964	7	23	30	NR	NR	NR	61	NR	9	NR	NR	NR
Round Top	USA	1,034	107	103	7	93	100	NR	NR	NR	NR	NR	NR	NR	NR	NR
Kvanefjeld	Greenland	619	86	139	NR	36	36	NR	NR	9	NR	55	NR	NR	NR	NR
Tantalus	Madagascar	435	66	151	15	16	32	NR	2	0.3	46	5	NR	2	13	Sn (0.2%)
Bear Lodge	USA	52	60	1,152	86	12	98	NR	2	0.5	NR	NR	NR	NR	NR	NR
Mount Weld CLD	Australia	15	56	3,732	92	7.6	100	NR	NR	NR	NR	NR	NR	NR	NR	NR
Nolans Bore	Australia	47	50	1,057	88	10	98	NR	NR	1	NR	NR	NR	NR	NR	P_2O_5 (1%)
Jabal Sa'id Zr	Saudi Arabia	23	48	2,082	1	15	16	NR	2	0.4	78	3	NR	1	NR	Sn (0.2%)

Note: This table gives an indication of the relative value of the REE and other elements within a given project; for example, some 85% of the value of the Bayan Obo resource is attributed to the LREE contained within the deposit, whereas Fe only makes up some 2% of the value of the deposit at current prices; economic values are based on 2013 price data from the USGS (1997–2015) and are intended to be indicative only; the prices of metals used in these calculations were obtained from HEFA (2014), LME (2014), and AM (2014); NR = not reported

Mt of contained REE resources have been deposited within the tailings at the site since this plant became operational (Cheng et al., 2007; Gao, 2009). In addition, the Cu-U-Au-Ag mine at Olympic Dam has produced some 136.6 Mt of tailings, which, assuming a resource grade of 0.5% TREO + Y, yields some 0.68 Mt of contained TREO + Y within tailings at the site (data updated from Mudd, 2014). Other smaller but better constrained resources are also known, including the Mary Kathleen U mine that closed in 1982 but has approximately 5.5 Mt of tailings on site at a grade of 6.4% TREO + Y (McKay et al., 2013). Another good example of potentially reprocessing mine tailings for REE production is the monazite produced during HMS mining, as HMS projects generally contain small amounts of monazite (~0.01–0.2%, depending on regional and deposit geology) that can be readily separated during mining. In India, monazite is the principal ore mineral used for REE extraction (10.7 Mt monazite mineral resources in 2012; IBM, 2014), and Australia exported monazite concentrates from HMS projects between the 1960s and the mid-1990s (Fig. 1), although all monazite produced in Australia is now either sent to tailings or managed as low-level radioactive waste. As summarized in our dataset, Australian HMS deposits potentially contain some 5.6 Mt TREO + Y (assuming that they contain monazite with 55% TREO + Y). However, although tailings may appear an attractive target for REE extraction, they could also contain high levels of radioactive elements such as Th and U. This, plus the fact that extraction of the REE from tailings, especially monazite tailings, is still challenging and costly, means that these resources remain only a theoretical possibility (Zhang et al., 2006; Pal et al., 2011), with significant uncertainties needing to be quantified before these potential REE resources could be efficiently extracted.

Declining ore grades, increasing energy costs, and the increasing awareness of the social and environmental impacts associated with mining and processing have raised significant concerns within and outside of the global mining industry (e.g., Mudd, 2010a, b; Banks, 2013). The fact that REE orebodies often require site-specific mining, refining, and processing systems means that the corresponding environmental impacts vary from deposit to deposit and are controlled by variations in REE content, mineralogy, mining, and refining technology. Various leaching techniques are often used in REE mining (e.g., differences between Bayan Obo and Mountain Pass, as discussed above, among others), with open-cut mining and traditional heap leaching-based production of 1 t TREO + Y from ion-adsorption rare earth mineralization (e.g., southern China) associated with the removal of 300 m^3 of topsoil and the generation of 2,000 t of tailings and 1,000 t of wastewater containing high concentrations of ammonium sulfate and heavy metals (Yang et al., 2013). REE mining also poses potential public health risks as the REE can potentially accumulate in anthropogenic environments, primarily as these elements are generally immobile (d'Aquino et al., 2009). Low-level REE accumulations in soils, vegetables, human hair, and blood have been documented in Hetian, a major center of ion-adsorption clay rare earth mining (Li et al., 2013). Although these accumulations do not exceed current safe values for estimated daily intake, the long-term exposure and corresponding chronic health impact of these accumulations remain highly contentious (Li et al., 2013).

The production of radioactive mine waste and the processing of radioactive ore during REE mining, especially during the exploitation of Th- and U-bearing mineralization (e.g., monazite stockpiles in India, at Steenkampskraal in South Africa, and at Mary Kathleen in Australia), also present significant environmental and health risks. This is exemplified by the fact that, without proper isolation and treatment of these radioactive wastes, REE production at individual or groups of mines could be suspended or even stopped as a result of social and/or environmental impacts. The Mountain Pass mine, which provided 100% of United States and 33% of global REE production between the 1960s and the 1980s, suspended production in 1998 (Wilburn, 2012) as a result of a combination of radioactive waste water leakage and the low price of the REE at that time. The EPA reports that the radiation levels from waste rock and sludge associated with REO production in the United States range from 0.21 to 119.3 Bq/g (USEPA, 2012), with additional treatment circuits generally required to precipitate radium from tailings and further controls needed to manage radon and associated decay products, all of which add to the costs involved in REE production. Long-term exposure to Th-enriched silica dust can also severely impact human health, with research by Chen et al. (2005) identifying that workers involved in the crushing stage of operations at Bayan Obo have a significantly higher Th lung burden (1.71 Bq/person) than miners involved in the other stages of operation (0.39–0.68 Bq/person). These data mean that these crushing-focused miners have a lung cancer standardized mortality ratio (SMR)—an indication of the ratio of observed mortalities in the study group to expected deaths in the general population (Brian and Anders, 2010)—which is almost double compared to that of miners elsewhere at Bayan Obo (5.5 compared to 2.3).

Some of these issues were evident in the 1982 commencement of operations at a monazite refining plant producing REE and Y owned by Asian Rare Earth (ARE) near Bukit Merah in Malaysia, an area that was poorly regulated, which caused serious environmental impacts and led to health concerns among workers and the local community, all of which caused the plant to shut in 1992 (Ichihara and Harding, 1995). Despite the short lifetime of production and the fact that the plant closed, the local community is still being affected by the cumulative exposure to radioactive waste in the area, especially to high concentrations of Th (Ichihara and Harding, 1995). The challenges faced by the development of REE projects are also illustrated by the problematic establishment of the Lynas Advance Materials Plant (LAMP) at Gebeng, Malaysia, a development that has caused widespread public protests about radiation safety, the environmental impact of the plant, and insufficient communication of relevant information to the local community (Golev et al., 2014). As summarized in IAEA (2011b), although the plant complied with international radiation safety standards, there were 10 issues that the LAMP facility needed to address, including a long-term waste management plan, the management of water leach purification solids after plant closure, a decommissioning and dismantling plan, a radiation exposure and environmental monitoring plan, a general improvement in the transparency of regulatory actions, and an increase in community communications (IAEA, 2011b). These issues illustrate the problems involved

in the development of new REE projects, especially as these projects usually involved both radioactive mineralization and high-energy and -chemical intensity mineral processing.

In summary, these brief case studies clearly suggest that social and environmental impacts, especially water and land contamination, radioactive wastes, and the chronic health issues associated with REE mining, are substantial risks to future REE production, in turn indicating that the management and mitigation of these inevitable risks are determining factors in the future of REE mining.

Conclusions

To establish a rigorous foundation for REE industries and governments to assess opportunities and challenges for future global REE supply, our study presents a comprehensive overview of global REE mineral resources by establishing an explicit and quantitative REE resource dataset. The 267 REE projects within the database are classified by deposit type and mineralogy, and include information on grades, principal by-/co-products, and individual REE abundances within both current and potential global REE resources, reported using statutory mining reporting systems. Our data indicate a minimum total global REE mineral resource of 619.5 Mt TREO + Y, with the 260 of the 267 deposits within our database that contain grade and tonnage data consisting of some 88,483 Mt of resources at an average concentration of 0.63% TREO + Y. Future global supply of the REE will be dominated by carbonatite projects that produce REE from bastnäsite, with potential REE production from various countries (e.g., Australia, Brazil, Canada, Greenland, and Russia) and several types of deposits (e.g., tailings, lateritic or clay-related deposits, IOCG, and alkaline complex and pegmatite) potentially becoming a significant source of the REE, including REE extraction from monazite obtained from HMS projects and reprocessing of existing mine tailings.

The data presented in this study indicate that current REE resources are dominated by the LREE, with an average light rare earth oxides (La-Gd) to heavy rare earth oxides (Tb-Lu and Y oxides) ratio of 13:1. These resources could sufficiently sustain global demand, with an optimistic scenario of 5% annual growth, until 2100 at a 2012 global production rate of 110 kt TREO + Y. From a mineral resources perspective, REE mineral resource scarcity and depletion is not likely to be the main constraint on the future supply of the REE; instead, major challenges for future REE industry are embodied in the geologic inequality of REE mineral resources (especially HREE) and relative processing difficulties, ascending demands of high-purity products of certain REE with low geologic abundances (e.g., Dy, Nd, Tb, etc.), inefficient and complicated by-/co-product elements (e.g., Nb, Sc, etc.) separation or purification, and the treatment and removal (either for sale or for safe disposal) of radioactive impurities (especially Th and U).

Finally, as evidenced by several historical or current REE projects, including both Mountain Pass and Bayan Obo, the crucial uncertainties and constraints for future global REE production are likely to be economic, mining, mineral processing, site-specific environmental impact, energy and chemical efficiency, and social in nature, rather than related to a lack of known resources or exploration success.

REFERENCES

Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., and Kirchain, R.E., 2012, Evaluating rare earth element availability: A case with revolutionary demand from clean technologies: Environmental Science and Technology, v. 46, p. 3406–3414.

AM, 2014, Metal price: Asian Metal (AM), Online database, www.asianmetal.com.

ASNO, 2014, Annual report 2013–2014: Australian Safeguards and Non-Proliferation Office (ASNO), 119 p.

AusIMM, Minerals Council of Australia (MCA), and Australian Institute of Geoscientists (AIG), 2012, Australasian code for reporting of exploration results, mineral resources and ore reserves: The JORC code, 2012 edition: Parkville, VIC, Joint Ore Reserves Committee (JORC) of AusIMM, MCA, and AIG, 44 p.

Banks, G., 2013, Little by little, inch by inch: Project expansion assessments in the Papua New Guinea mining industry: Resources Policy, v. 38, p. 688–695.

Bau, M., Schmidt, K., Koschinsky, A., Hein, J., Kuhn, T., and Usui, A., 2014, Discriminating between different genetic types of marine ferro-manganese crusts and nodules based on rare earth elements and yttrium: Chemical Geology, v. 381, p. 1–9.

BHPB, 2011a, Annual report—2011: Adelaide, SA, Australia, BHP Billiton Ltd., 36 p.

——2011b, Olympic Dam expansion—supplementary environmental impact statement: Adelaide, SA, 2011, BHP Billiton Ltd., 891 p.

——2012, Annual report—2012: Adelaide, SA, Australia, BHP Billiton Ltd., 276 p.

BoMRGG, 1960–1985, The Australian mineral industry review (years 1960 to 1985): Australia, Bureau of Mineral Resources, Geology and Geophysics.

Brian, S.E., and Anders, S., 2010, Standardized mortality rate (SMR), in Brian, S.E., ed., The Cambridge dictionary of statistics: New York, Cambridge University Press, p. 409.

Britt, A., Whitaker, A., Cadman, S., Summerfield, D., Kay, P., Champion, D., McKay, A., Miezitis, Y., Porritt, K., Schofield, A., and Jaireth, S., 2015, Australia's identified mineral resources 2014: Canberra, Australia, Geoscience Australia, 16 p.

Chakhmouradian, A.R., and Zaitsev, A.N., 2012, Rare earth mineralization in igneous rocks: Sources and processes: Elements, v. 8, p. 347–353.

Chen, X.A., Cheng, Y.E., and Rong, Z., 2005, Recent results from a study of thorium lung burdens and health effects among miners in China: Journal of Radiological Protection, v. 25, p. 451–460.

Cheng, J.Z., Hou, Y.B., and Ju, L.P., 2007, Comprehensive development and utilization of Baiyun Obo ore body: Chinese Rare Earths, v. 28, p. 70–73. (in Chinese)

Christie, T., Brathwaite, B., and Tulloch, A., 1998, Mineral commodities report 17—rare earths and related elements: Auckland, New Zealand, New Zealand Institute of Geological and Nuclear Sciences Ltd, 13 p.

CSRE, 2002, Chinese Rare Earth Society yearbook 2002: Beijing, China, Chinese Society of Rare Earths, 306 p.

d'Aquino, L., Morgana, M., Carboni, M.A., Staiano, M., Antisari, M.V., Re, M., Lorito, M., Vinale, F., Abadi, K.M., and Woo, S.L., 2009, Effect of some rare earth elements on the growth and lanthanide accumulation in different Trichoderma strains: Soil Biology and Biochemistry, v. 41, p. 2406–2413.

Eccles, R., Nicholls, S., McMillan, K., and Dufresne, M., 2013, National Instrument 43-101 technical report updated and expanded mineral resource estimate for the Buckton zone, SBH property, northeast Alberta: Toronto, Canada, APEX Geoscience Ltd., 137 p.

Ernst, R.E., and Jowitt, S.M., 2013, Large igneous provinces (LIPs) and metallogeny, in Colpron, M., Bissig, T., Rusk, B.G., and Thompson, J.F.H., eds., Tectonics, metallogeny, and discovery: The North American Cordillera and similar accretionary settings: Society of Economic Geologists Special Publication 17, p. 17–51.

Gao, H.Z., 2009, General comments on rare earth and scarce resources in Bayan Obo: Science and Technology of Baotou Steel (Group) Corporation, v. 35, p. 1–6. (in Chinese)

Golev, A., Scott, M., Erskine, P.D., Ali, S.H., and Ballantyne, G.R., 2014, Rare earth supply chains: Current status, constraints and opportunities: Resources Policy, v. 41, p. 52–59.

Gupta, C.K., and Krishnamurthy, N., 2005, Extractive metallurgy of rare earths: Boca Raton, CRC Press, 508 p.

Hayes-Labruto, L., Schillebeeckx, S.J.D., Workman, M., and Shah, N., 2013, Contrasting perspectives on China's rare earths policies: Reframing the debate through a stakeholder lens: Energy Policy, v. 63, p. 55–68.

HEFA, 2014, Rare earth metal prices: HEFA Rare Earth Inc., www.mineral prices.com.

Hellman, P.L., and Duncan, R.K., 2014, Evaluation of rare earth element deposits: IMM Transactions B: Applied Earth Science, v. 123, p. 107–117.

Hoatson, D.M., Jaireth, S., and Miezitis, Y., 2011, The major rare earth element deposits of Australia: Geological setting, exploration, and resources: Canberra, ACT, Geoscience Australia, 204 p.

Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F., and Graus, W., 2013, Can a dysprosium shortage threaten green energy technologies?: Energy, v. 49, p. 344–355.

Humphries, M., 2013, Rare earth elements: The global supply chain: Washington, US Congressional Research Service, 27 p.

IAEA, 2011a, Radiation protection and NORM residue management in the production of rare earths from thorium containing minerals: Vienna, International Atomic Energy Agency, Safety Reports Series No. 68, 259 p.

——2011b, Report of international review mission on the radiation safety aspects of a proposed rare earths processing facility (the Lynas project): 29 May–3 June 2011 Malaysia: International Atomic Energy Agency, 57 p., www.iaea.org/sites/default/files/lynasreport2011.pdf

IBM, 2014, Indian minerals yearbook 2012, rare earths: India, Indian Bureau of Miners, 7 p.

Ichihara, M., and Harding, A., 1995, Human rights, the environment and radioactive waste: A study of the Asian Rare Earth case in Malaysia: Review of European Community and International Environmental Law, v. 4, p. 1–14.

IUPAC, 2005, Nomenclature of inorganic chemistry IUPAC recommendations 2005: Cambridge, UK, International Union of Pure and Applied Chemistry, 366 p.

Jones, A.P., Wall, F., and Williams, C.T., 1996, Rare earth minerals: Chemistry, origin and ore deposits: London, UK, Mineralogical Society, Chapman and Hall, 377 p.

Jordan, S.C., Jowitt, S.M., and Cas, R.A.F., 2015, Origin of temporal-compositional variations during the eruption of Lake Purrumbete Maar, Newer Volcanics Province, southeastern Australia: Bulletin of Volcanology, v. 77, p. 1–15.

Jordens, A., Cheng, Y.P., and Waters, K.E., 2013, A review of the beneficiation of rare earth element bearing minerals: Minerals Engineering, v. 41, p. 97–114.

Jowitt, S.M., Mudd, G.M., and Weng, Z., 2013a, Hidden mineral deposits in Cu-dominated porphyry-skarn systems: How resource reporting can occlude important mineralization types within mining camps: Economic Geology, v. 118, p. 1185–1193.

Jowitt, S.M., Weng, Z., and Mudd, G., 2013b, Rare earth elements: Deposits, uncertainties and wasted opportunities. Materials World, v. 21, p. 22–24.

Kato, Y., Fujinaga, K., Nakamura, K., Takaya, Y., Kitamura, K., Ohta, J., Toda, R., Nakashima, T., and Iwamori, H., 2011, Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements: Nature Geoscience, v. 4, p. 535–539.

Lai, X., and Yang, X., 2013, Geochemical characteristics of the Bayan Obo giant REE-Nb-Fe deposit: Constraints on its genesis: Journal of South American Earth Sciences, v. 41, p. 99–112.

Li, X., Chen, Z., Chen, Z., and Zhang, Y., 2013, A human health risk assessment of rare earth elements in soil and vegetables from a mining area in Fujian Province, southeast China: Chemosphere, v. 93, p. 1240–1246.

LME, 2014, Metal pricing and historical data: London, UK, LME (London Metal Exchange), www.lme.com.

Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, D., 2010, The principal rare earth deposits of the United States—a summary of domestic deposits and a global perspective: USGS Scientific Investigations Report 2010-5220, 96 p.

McKay, A.D., Meizitis, Y., Porritt, K., Champion, D.C., Britt, A., Whitaker, A., Summerfield, D., Sexton, M., Jaireth, S., Huston, D., Hoatson, D., Schofield, A., Carson, L., Towner, R., and Huelatt, M., 2013, Australia's identified mineral resources 2012: Canberra, Australia, Geoscience Australia, 162 p.

McPhie, J., Kamenetsky, V., Allen, S., Ehrig, K., Agangi, A., and Bath, A., 2011, The fluorine link between a supergiant ore deposit and a silicic large igneous province: Geology, v. 42, p. 1003–1006.

Medlin, C.C., Jowitt, S.M., Cas, R.A.F., Smithies, R.H., Kirkland, C.L., Maas, R.A., Raveggi, M., Howard, H.M., and Wingate, M.T.D., 2015, Petrogenesis of the A-type, Mesoproterozoic intra-caldera rheomorphic Kathleen Ignimbrite and co-magmatic Rowland Suite intrusions, west Musgrave Province, central Australia: Products of extreme fractional crystallisation in a failed rift setting: Journal of Petrology, v. 56, p. 493–525.

Moldoveanu, G.A., and Papangelakis, V.G., 2012, Recovery of rare earth elements adsorbed on clay minerals: I. Desorption mechanism: Hydrometallurgy, v. 117–118, p. 71–78.

MoLRPRC, 2012, The case study of comprehensive implementation of mineral resources in Bayan Obo Iron deposit includes rare earth elements, niobium and thorium, 2014: Beijing, China, Ministry of Land and Resources of the People's Republic of China, 2 p.

Morrison, W.M., and Tang, R., 2012, China's rare earth industry and export regime: Economic and trade implications for the United States: Washington, US Congressional Research Service, 17 p.

Moss, R.L., Tzimas, E., Kara, W.P., and Kooroshy, J., 2011, Critical metals in strategic energy technologies: Luxembourg, European Commission Joint Research Centre, Institute for Energy and Transport, 161 p.

Moss, R.L., Tzimas, E., Kara, H., Willis, P., and Kooroshy, J., 2013a, The potential risks from metals bottlenecks to the deployment of strategic energy technologies: Energy Policy, v. 55, p. 556–564.

Moss, R.L., Tzimas, E., Kara, H., Willis, P., Arendorf, J., and Tercero Espinoza, L., 2013b, Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies: Critical metals in the path towards the decarbonisation of the EU energy sector: Luxembourg, European Commission Joint Research Centre, Institute for Energy and Transport, 246 p.

Mudd, G.M., 2010a, The environmental sustainability of mining in Australia: Key mega-trends and looming constraints: Resources Policy, v. 35, p. 98–115.

——2010b, Global trends and environmental issues in nickel mining: Sulfides versus laterites: Ore Geology Reviews, v. 38, p. 9–26.

——2014, The future of yellowcake: A global assessment of uranium resources and mining: Science of the Total Environment, v. 472, p. 590–607.

Mudd, G.M., Weng, Z., and Jowitt, S.M., 2013a, A detailed assessment of global Cu resource trends and endowments: Economic Geology, v. 108, p. 1163–1183.

Mudd, G.M., Weng, Z., Jowitt, S.M., Turnbull, I.D., and Graedel, T.E., 2013b, Quantifying the recoverable resources of by-product metals: The case of cobalt: Ore Geology Reviews, v. 55, p. 87–98.

Naden, J., 2014, Science and implementation plan security of supply of mineral resources (SoS Minerals) Research Programme 2012–2017: Nottingham, Natural Environment Research Council (NERC), British Geological Survey, 15 p.

Oreskes, N., and Einaudi, M.T., 1990, Origin of rare earth element-enriched hematite breccias at the Olympic Dam Cu-U-Au-Ag deposit, Roxby Downs, South Australia: Economic Geology, v. 85, p. 1–28.

OSC, 2011, National Instrument 43-101—standards of disclosure for mineral projects, form 43-101F1 and companion policy 43-101CP: Toronto, Canada, Ontario Securities Commission (OSC), 44 p.

Pal, D.C., Chaudhuri, T., McFarlane, C., Mukherjee, A., and Sarangi, A.K., 2011, Mineral chemistry and in situ dating of allanite, and geochemistry of its host rocks in the Bagjata uranium mine, Singhbhum shear zone, India—implications for the chemical evolution of REE mineralization and mobilization: Economic Geology, v. 106, p. 1155–1171.

Parhi, P.K., Park, K.H., Nam, C.W., Park, J.T., and Barik, S.P., 2013, Extraction of rare earth metals from deep sea nodule using H_2SO_4 solution: International Journal of Mineral Processing, v. 119, p. 89–92.

PCREML, 2012, Status summary of the Jongju REE target, Democratic People's Republic of Korea: Pacific Century Rare Earths Minerals Limited.

Reeves, J.S., Cross, K.C., Smith, R.N., and Oreskes, N., 1990, Olympic Dam copper-uranium-gold-silver deposit, in Hughes, F.E., ed., Geology of the mineral deposits of Australia and Papua New Guinea: Melbourne, Australian Institute of Mining and Metallurgy, p. 1009–1035.

Rudnick, R.L., and Gao, S., 2003, Composition of the continental crust, in Holland, H.D., and Turekian, K.K., eds., Treatise on geochemistry, 3: Oxford, Elsevier Pergamon, 56 p.

SAMRCWG, 2009, South African code for the reporting of exploration results, mineral resources and mineral reserves (the SAMREC Code): Johannesburg, South Africa, South African Mineral Resource Committee

Working Group, Southern African Institute of Mining and Metallurgy (SAIMM), and Geological Society of South Africa (GSSA), 61 p.

SCIO, 2012, Status and policies of China's rare earth industry: Beijing, SCIO (State Council Information Office of the People's Republic of China), 32 p.

Skirrow, R.G., Bastrakov, E.N., Barovich, K., Fraser, G.L., Creaser, R.A., Fanning, C.M., Raymond, O.L., and Davidson, G.J., 2007, Timing of iron oxide Cu-Au-(U) hydrothermal activity and Nd isotope constraints on metal sources in the Gawler craton, South Australia: Economic Geology, v. 102, p. 1441–1470.

Smith, M.P., Campbell, L.S., and 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, v. 64, p. 459–476.

Stephenson, P.R., 2001, The JORC Code: IMM Transactions B: Applied Earth Science, v. 110, p. 121–125.

USBoM, 1927–1934, Mineral resources of the United States (years 1927–1934): United States, U.S. Bureau of Mines.

——1933–1996, Minerals yearbook (years 1933–1996): United States, U.S. Bureau of Mines.

USDOE, 2010, Critical mineral strategies: U.S. Department of Energy, 165 p.

USEPA, 2012, Rare earth elements: A review of production, processing, recycling, and associated environmental issues: Cincinnati, U.S. Environmental Protection Agency (USEPA), 135 p.

USGS, 1901–1927, Mineral resources of the United States (years 1901–1927): United States, U.S. Geological Survey.

——1994–2011, Minerals yearbook (years 1994–2011): Reston, Virginia, U.S. Geological Survey.

——1997–2015, Minerals commodity summaries (years 1997–2015): Reston, Virginia, U.S. Geological Survey.

van Emden, B., Thornber, R.M., Graham, J., and Lincoln, J.F., 1997, The incorporation of actinides in monazite and xenotime from placer deposits in Western Australia: Canadian Mineralogist, v. 35, p. 95–104.

Walters, A., Lusty, P., Chetwyn, C., and Hill, A., 2010, Rare earth elements, mineral profile series: United Kingdom, British Geological Survey, 53 p.

Weng, Z.H., Jowitt, S.M., Mudd, G.M., and Hague, N., 2013, Assessing rare earth element mineral deposit types and links to environmental impacts: Transactions of the Institute of Mining and Metallurgy B: Applied Earth Science, v. 122, p. 83–96.

Wilburn, D.R., 2012, Byproduct metals and rare-earth elements used in the production of light-emitting diodes-overview of principal sources of supply and material requirements for selected markets: U.S. Geological Survey, Scientific Investigations Report 2012-5215, 15 p.

Williams-Jones, A.E., Migdisov, A.A., and Samson, I.M., 2012, Hydrothermal mobilisation of the rare earth elements—a tale of "Ceria" and "Yttria": Elements, v. 8, p. 355–360.

WTO, 2014, China—measures related to the exportation of rare earths, tungsten, and molybdenum: World Trade Organization, Reports of the Panel, WT/DS431-3/R, 257 p.

Wübbeke, J., 2013, Rare earth elements in China: Policies and narratives of reinventing an industry: Resources Policy, v. 38, p. 384–394.

Yang, K.-F., Fan, H.-R., Santosh, M., Hu, F.-F., and Wang, K.-Y., 2011, Mesoproterozoic carbonatitic magmatism in the Bayan Obo deposit, Inner Mongolia, north China: Constraints for the mechanism of super accumulation of rare earth elements: Ore Geology Reviews, v. 40, p. 122–131.

Yang, S.Y., Jung, H.S., Choi, M.S., and Li, C.X., 2002, The rare earth element compositions of the Changjiang (Yangtze) and Huanghe (Yellow) river sediments: Earth and Planetary Science Letters, v. 201, p. 407–419.

Yang, X.J., Lin, A., Li, X.-L., Wu, Y., Zhou, W., and Chen, Z., 2013, China's ion-adsorption rare earth resources, mining consequences and preservation: Environmental Development, v. 8, p. 131–136.

Yang, X.-M., and Le Bas, M.J., 2004, Chemical compositions of carbonate minerals from Bayan Obo, Inner Mongolia, China: Implications for petrogenesis: Lithos, v. 72, p. 97–116.

Zhang, S., Xue, X., Liu, X., Duan, P., Yang, H., Jiang, T., Wang, D., and Liu, R., 2006, Current situation and comprehensive utilization of iron ore tailings resources: Journal of Mining Science, v. 42, p. 403–408.