

# Geology and market-dependent significance of rare earth element resources

G. J. Simandl

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**Abstract** China started to produce rare earth elements (REEs) in the 1980s, and since the mid-1990s, it has become the dominant producer. Rare earth element export quotas first introduced by the Chinese government in the early 2000s were severely reduced in 2010 and 2011. This led to strong government-created disparity between prices within China and the rest of the world. Industrialized countries identified several REEs as strategic metals. Because of rapid price increases of REE outside of China, we have witnessed a world-scale REE exploration rush. The REE resources are concentrated in carbonatite-related deposits, peralkaline igneous rocks, pegmatites, monazite ± apatite veins, ion adsorption clays, placers, and some deep ocean sediments. REE could also be derived as a by-product of phosphate fertilizer production, U processing, mining of Ti-Zr-bearing placers, and exploitation of Olympic Dam subtype iron oxide copper gold (IOCG) deposits. Currently, REEs are produced mostly from carbonatite-related deposits, but ion adsorption clay deposits are an important source of heavy REE (HREE). Small quantities of REE are derived from placer deposits and one peralkaline intrusion-related deposit. The ideal REE development targets would be located in a politically stable jurisdiction with a pro-mining disposition such as Canada and Australia. REE grade, HREE/light REE (LREE) ratio of the mineralization, tonnage, mineralogy, and permissive metallurgy are some of the key technical factors that could be used to screen potential development projects. As REEs are

considered strategic metals from economic, national security, and environmental points of view, technical and economic parameters alone are unlikely to be used in REE project development decision-making. Recycling of REE is in its infancy and unless legislated, in the short term, it is not expected to contribute significantly to the supply of REE.

**Keywords** Rare earth elements · Ion adsorption clay · Carbonatite · Peralkaline intrusion · Placer · Skarn · Monazite ± apatite vein · Phosphate · Uranium

## Introduction

According to the International Union of Pure and Applied Chemistry (Connelly et al. 2005), the term “rare earth elements” (REEs) encompass yttrium (Y), scandium (Sc), and the lanthanides lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

REEs are commonly subdivided into light (LREE) and heavy (HREE) categories. Within the scientific community, the boundary between HREE and LREE is based on the electron configuration of individual REE. The term LREE covers the La-Gd portion of the lanthanide series (atomic numbers 57–64). Lanthanum has no 4f shell electrons, and one clockwise-spinning electron is added to each subsequent lanthanide until Gd (heaviest of LREE) is reached. The term HREE covers the Tb-Lu portion of the lanthanide series (atomic numbers 65–71) plus Y (atomic number 39). Starting with Tb, one counter clockwise-spinning electron is added to each subsequent lanthanide until Lu is reached. Therefore, HREE differ from LREE by having “paired” (both clockwise- and counter clockwise-spinning) electrons

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G. J. Simandl (✉)  
British Columbia Ministry of Energy and Mines, PO Box 9333 Stn  
Prov. Govt., Victoria V8W 9N3, Canada  
e-mail: george.simandl@gov.bc.ca

G. J. Simandl  
School of Earth and Ocean Sciences, University of Victoria, PO Box  
1700 STN CSC, Victoria V8W 2Y2, Canada

(Cordier 2011). Yttrium is grouped with HREE based on its similar ionic radius and similar chemical properties. The properties of Sc are too different from the lanthanides to be assigned to either HREE or LREE. Promethium (Pm) is a radioactive element with a very short half-life, mainly produced in nuclear reactors; natural Pm is exceedingly scarce on Earth.

The mining industry commonly assigns the term LREE to cover lanthanides with an atomic number equal to or lesser than 62 (La, Ce, Pr, Nd, Sm), and the term HREE includes lanthanides with an atomic number of 63 or larger (Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu), plus Y. This practice started in the mid-2000s to increase the apparent HREE/LREE ratio of any ore, making it appear more attractive for potential investors. The expression “total rare earth oxides” (TREO) used in ore reserve estimates refers to the sum of individual REO concentrations including  $Y_2O_3$  unless otherwise specified. It is reported in weight percent (wt%).

Concentrations of individual LREE in the upper crust of the Earth are comparable to those of base metals, and even the least abundant REE (Lu) is about 200 times more abundant than gold (Haxel et al. 2002). A large proportion of REEs are present in low concentrations within the structure of rock-forming minerals, in high concentrations in REE minerals that are difficult to process, or in accessory minerals, which, by definition, are present in low concentrations in common rocks.

China surpassed USA as the largest REE producer in the mid-1990s. At that time, Chinese REE producers had a competitive edge over western producers due to inexpensive and abundant labor, low-energy costs, and lack of environmental requirements (Folger 2011). It may be a coincidence that export quotas and licensing for REE were introduced in 1999, during a period when the Chinese government was enticing high technology companies to establish their new production facilities in its country. The systematic reduction in Chinese export quotas started in 2006 and the historic 40 % reduction took place in 2010 (Wübbecke 2013). Chinese REE production quotas came into effect in 2009. Temporary interruption of REE exports to Japan during the 2010 dispute over maritime boundaries (Bradsher 2010; Areddy et al. 2010), later officially denied by the Chinese government, highlighted the vulnerability of western high technology industries to disruptions of critical materials such as REE. The main motive (be it economic, environmental, or social) of the Chinese government behind the introduction of the export and production quotas and new REE-related policies aiming to consolidate the Chinese REE industry is contested and open to interpretation (Hayes-Labruzzo et al. 2013). Regardless of the motive(s) behind REE export quotas and related policies, a two-tier REE pricing system was established. As a result, in April 2014, high technology plants operating in China benefited from a 40 % discount in La and Ce oxide prices, over 20 % discount in Pr, Nd, Eu, and Dy oxide prices and 50 % or more

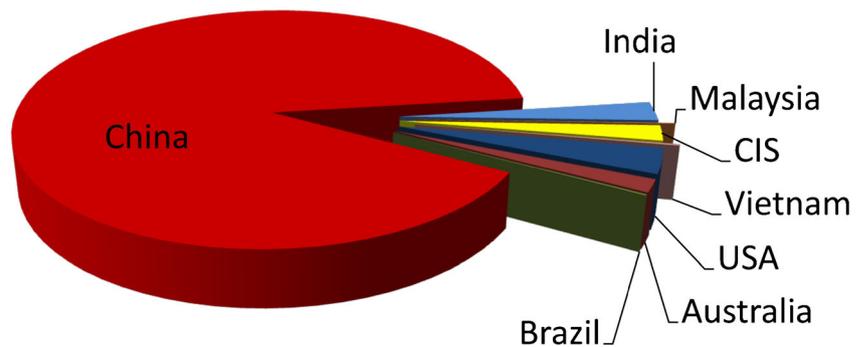
in Y and Sm oxide prices relative to export (free on board China) prices (Els 2014), providing a powerful economic advantage for REE-intensive manufacturing facilities operating in China.

The 2013 world production of REE, including Y, reported in the form of oxides (REO) is estimated at 120,000 t (Fig. 1). This estimate is based on published United States Geological Survey (USGS) data (Gambogi 2014a,b) in combination with an unpublished 2013 Roskill estimate for the Commonwealth of Independent States. Although high technology industries can substitute several REEs with other materials, these substitutes are typically more expensive or less effective than the REE they replace. A number of countries, including the USA, consider several REEs essential for national security, their economy, and the reduction of greenhouse gas emissions. The forecasted demand for individual LREO is much higher than that of HREO (Fig. 2). Dysprosium, Eu, Tb, Nd, and Y are essential for the US and European economies and subject to predicted supply disruptions (US Department of Energy 2010, 2011; European Commission 2010). Recent prices of selected REE and REO are provided in Table 1. The prices of REO reached an all time high during the summer of 2011, since that time they were on the downturn; however, they are starting to stabilize (Fig. 3). Such abrupt variations in prices of specialty metals and some industrial minerals are common as illustrated by the 2000 spike in  $Ta_2O_5$  prices (Fig. 2, Mackay and Simandl, this volume). The prices of LREO may dip even lower if the recent ruling of the World Trade Organization is upheld (Syrett 2013a), if China eliminates or loosens export quotas for REE to eliminate competition from deposits currently under development outside of China, if new government-supported mines outside of China reach production stage, or if efforts to reduce the use of REE in the automotive industry (Syrett 2013b) are successful.

### Current and future sources of REE

China started to produce REE in the 1980s, and since the mid-1990s, it has become the dominant producer (Haxel et al. 2002). China controls the world REE market; however, small quantities come from the Commonwealth of Independent States (CIS), USA, Australia, India, Brazil, Malaysia, and a few other countries (Fig. 1). REE export quotas established by China favored high technology investment in China relative to other parts of the world and led to rapid increases in the price of REE outside of China (Simandl 2010). Most LREE production in China comes from the Bayan Obo deposit in Inner Mongolia. Bayan Obo is a carbonatite-related distal hydrothermal Fe-Nb-REE deposit. In 2008, it produced 60,000–70,000 t of REO with a Fe co-product. A few carbonatite-hosted deposits also contribute to LREE production but to a much smaller extent (~15,000 t of REO). Ion adsorption clay

**Fig. 1** World rare earth oxide (REO) production for 2013 subdivided according to geographic location. Data from Gambogi (2014a, b), unpublished information from Roskill Information Services regarding the Commonwealth of Independent States



deposits contribute significantly to LREE production and represent a principal source of HREE (20,000–40,000 t of total REO), but production is on the decline. There was virtually no REE recycling prior to 2008 (Goonan 2011). Recent examples of REE recycling-related research are described by Anderson et al. (2012), Weltevreden et al. (2012), Grabas et al. (2012), and Resende and Morais (2012). REE recycling on the laboratory or small industrial scale takes place in Europe and Japan; however, it could become more viable if high prices, similar to those witnessed during 2011, become the market norm, or if it becomes mandated by governments.

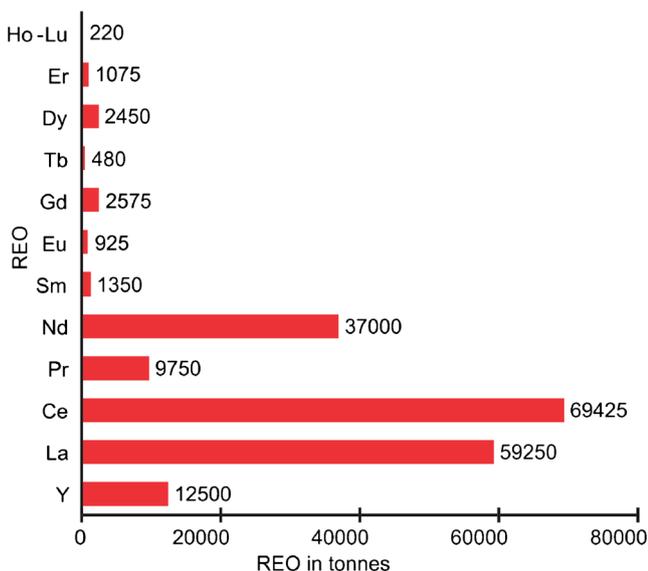
According to recent USGS estimates (Gambogi 2014a, b), world REEs including Y “reserves” (as defined by USGS) are approximately 140 million t. Most of these “reserves” are located in China, Brazil, USA, India, and Australia (Fig. 4). The definition of ore reserves used by the USGS is not compliant with the reporting standards mandated by the NI-43-101 and Joint Ore Reserves Committee (JORC) codes. Estimates of ore “reserves” by the USGS may not even satisfy the definition of “resources” under NI-43-101 and JORC

codes. Consequently, the importance of Canada and Australia relative to the above-listed jurisdictions is probably strongly underestimated.

More than 556 REE-oriented exploration projects were active worldwide in 2012. Of these, 296 were grassroots projects (no drilling), 157 had limited drilling, 66 were at an advanced exploration stage, 26 were at the pre-feasibility stage, 7 were at the feasibility stage, and 4 operations were under construction (Intierra 2012). Of the 54 projects covered by announcements of new drilling results, 19 were located in Canada and 12 in Australia (Intierra 2012). Most of the 63 advanced projects listed by TMR technology metal research in 2014 are located in Canada (33 %), Australia (16 %), USA (10 %), South Africa (8 %), and Greenland (8 %). The remaining projects are located in Brazil, Malawi, Kenya, Tanzania, Madagascar, Sweden, Mozambique, Kyrgyzstan, Namibia, and Germany (Hatch 2014).

**REE-bearing deposits**

REE-bearing deposit types can be classified based on the association between mineralization and host rock. In this classification, deposits in which REE are the main (or principal) elements of economic interest are considered as primary REE exploration targets. Where REEs are subordinate

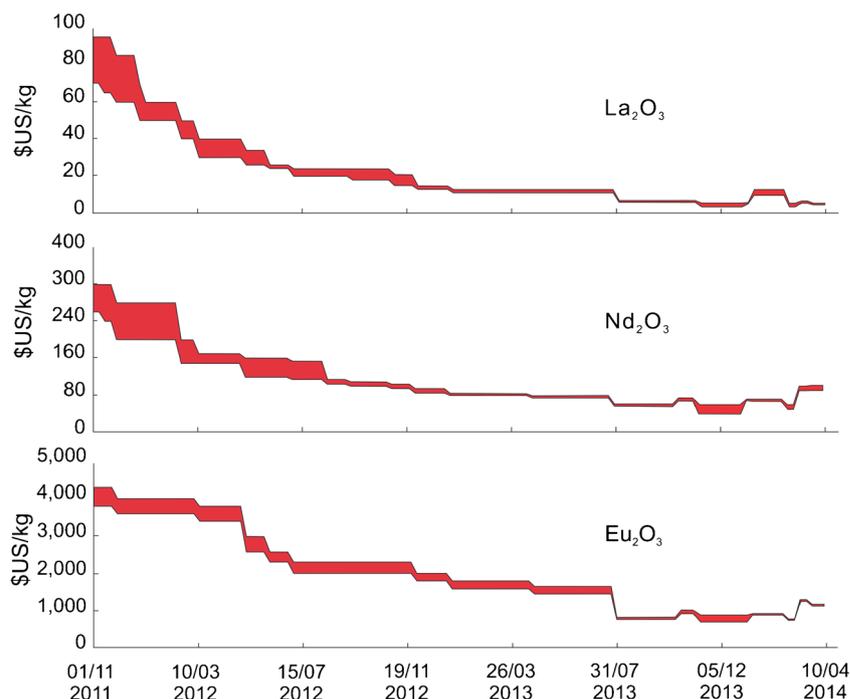


**Fig. 2** Forecasted 2014 demand for individual REOs (modified from Watts 2010)

**Table 1** Recent prices of REE (metal) and REO for export. All prices reported in US\$/kg, free on board China for purity of 99.9 %. The exception is the Y oxide, where the minimum purity is 99.999 % (source of information: Asian Metal; November 11, 2013)

Element	Price (\$US/kg)	
	Metal	Oxide
Ce	11–14	6.5–7.5
Dy	650–700	490–540
Er	70–75	
Eu	1,250–1,300	950–1,000
La	10–13	5.5–6.5
Nd	100–104	70–75
Pr	152–162	117–122
Sm	33–36	7.2–8.0
Tb	950–1,050	750–850
Y	61–66	23–25

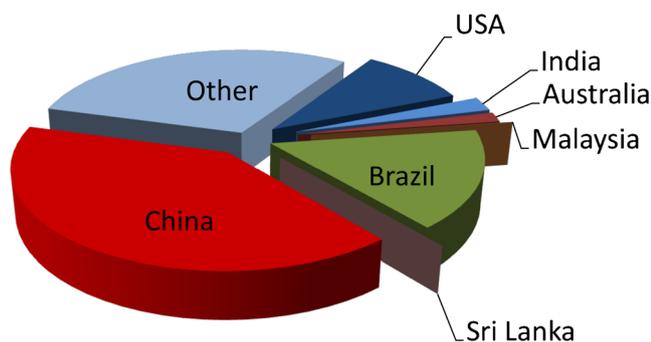
**Fig. 3** Variation in prices of La, Nd, and Eu oxides with time; minimum grade 99 % REO, free on board China, shipped in bulk. Prices of Ce and Pr oxides follow the same pattern as prices of La and Nd oxides, respectively. Since 2011, the decline in prices of heavy lanthanides was moderate relative to that of LREE. Source of data: Anonymous (2014)



(possible co-product commodities), deposits represent secondary sources or secondary REE exploration targets (Simandl et al. 2012b; Simandl 2010; 2012). These deposit types can be divided into three categories. The first category contains the deposits that are currently mined as principal sources of REE. This includes carbonatite-related deposits, ion adsorption clays, and placer deposits. The second category comprises deposits that contributed to historical production of REE such as monazite  $\pm$  apatite veins, REE-bearing uranium deposits, and phosphate rocks. The third category groups all remaining deposit types.

#### Carbonatite and carbonatite–syenite complex-related deposits

Carbonatites are defined as carbonate-rich, intrusive, or extrusive igneous rocks that comprise more than 50 % carbonate minerals (Woolley and Kempe 1989). However, some rocks



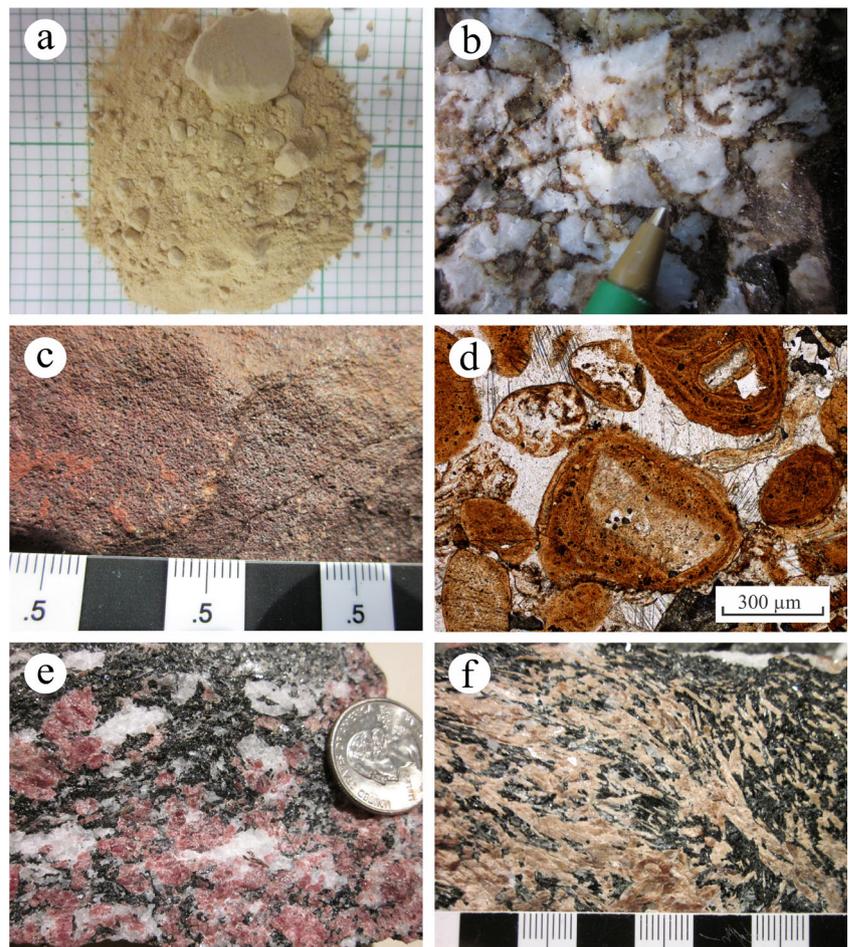
**Fig. 4** World REO including Y resources is estimated at 140,000,000 t. If these estimates are correct (see text), most resources are located in China, Brazil, and the USA (data from Gambogi 2014a, b)

identified in the field as carbonatites may be of carbothermal (formed from late low-temperature fluids derived from a fractionated magma, dominated by  $\text{CO}_2$  but also containing F and  $\text{H}_2\text{O}$ ) origin (Mitchel 2005). There are more than 527 carbonatite occurrences known worldwide (Wolley and Kjasgaard 2008). Carbonatites and related syenites form plugs, lopoliths, dikes, sills, cone sheets, or breccia zones and are associated with fenitization (Na, K, Fe alteration) of host rocks. They are commonly associated with major faulting, rift valleys, and lithosphere doming in stable continental intra-plate settings (Woolley and Kempe 1989; Wolley and Kjasgaard 2008); however, they are also known in continental plate margin settings. Many carbonatites are coeval with syenitic or ultramafic rocks. Carbonatite and associated alkaline rock-hosted deposits are known to contain economic concentrations of Nb ( $\pm$ Ta), REE, and, in some cases, Fe, Sr, Mo, Cu, U, Th, Ca, and Mg carbonates, fluorite, barite, vermiculite, and apatite (Mariano 1989a,b; Richardson and Birkett 1996a,b; Birkett and Simandl 1999).

Hogarth (1989) compiled a list of minerals reported in carbonatites and many of these minerals are REE-bearing. Some carbonatites contain spatially associated, discrete mineralized zones enriched in REE-bearing fluorocarbonate and/or monazite that are of economic interest.

Most of the world's LREE production comes from bastnaesite- and monazite-bearing carbonatite-related deposits, such as Bayan Obo (Inner Mongolia), Maoniuping (northern Panxi region), and bastnaesite-dominated (Fig. 5a) Mountain Pass (USA). Information regarding carbonatites and carbonatite-related REE deposits in China is summarized by Yang and Woolley (2006) and Kynicky et al. (2012),

**Fig. 5** Examples of concentrate and mineralization from selected REE-bearing deposits. **a** Bastnaesite concentrate from Mountain Pass (USA) containing 65 % total REO, millimetric paper for scale. **b** Surface sample of fracture controlled, REE mineralization in carbonatite (Wicheeda carbonatite complex, BC). **c** Red-stained monazite and apatite-rich mineralization (Steenkampskraal vein, SA). **d** Typical REE-bearing phosphate rock; REEs are in *honey brown-colored* francolite (BC). **e** Eudialyte (*red*) from Kipawa (QC). **f** Mosandrite (*beige*), Kipawa deposit (QC)



respectively. A number of carbonatite-related deposits outside of China, besides Mountain Pass, also contain REE-enriched zones and are being considered as potential sources of REE. Ququarssuk, Tikiusaaq, and Sarfartoq are located in Greenland (Sørensen and Kalvig 2011). In Canada, the Saint Honoré carbonatite, a current Nb producer, contains significant REE resources (total indicated and inferred resources of 531.4 million t grading 1.64 wt% TREO and 527.2 million t grading 1.83 wt% TREO, respectively; Grenier and Tremblay 2013). Other Canadian carbonatite-associated REE deposits that have received, or are receiving, serious attention are Eldor (QC), Wicheeda Lake (BC), Montviel (QC), among others (Simandl et al. 2012b, c).

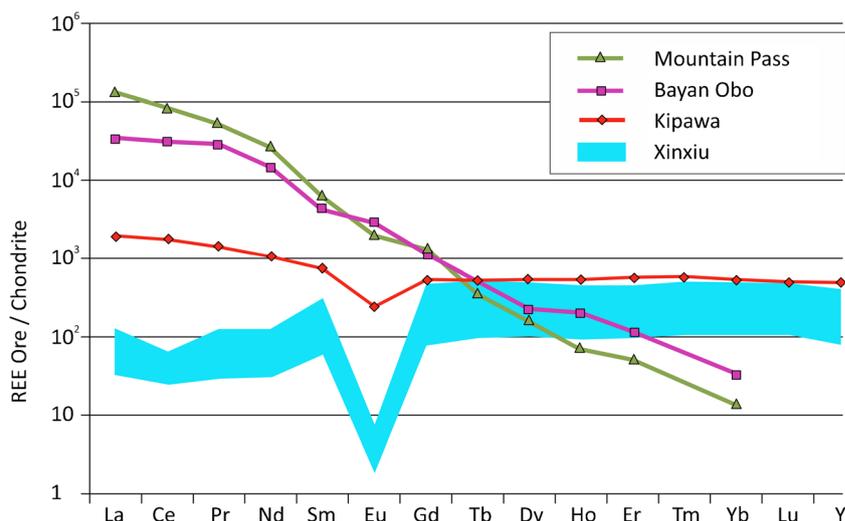
Figure 5b displays the typical appearance of dolomitic carbonatite. Carbonatite-related deposits are characterized by enrichment in LREE (Fig. 6). Some REE-bearing carbonatite-related deposits have been further enriched by surface weathering. Examples of these deposits include Mount Weld (Australia), Bear Lodge (USA), and Araxá (Brazil). The REEs in weathering-enriched portions of carbonatites are commonly fine-grained and texturally complex, displaying vertical mineralogical zonation (Mariano 1989b; Richardson and Birkett 1996b; Lottermoser 1990). Probably, the best documented

example of weathering-enriched carbonatite-related REE deposits is the Mount Weld carbonatite where the central lanthanide zone contains the main REE resource (Fig. 7; Duncan and Willet 1990; Lottermoser 1990). Undeveloped, weathering-enriched carbonatite zones have been historically considered to be metallurgically challenging sources of REE because of fine-grained (Lottermoser 1995) interlocking textures and zonation in mineralogy. The 2009–2011 rise in REO prices opened up the possibility for extraction of REE directly from “raw ore” without preconcentration; simultaneously, a number of new metallurgical processing flow sheets were developed to extract REE from weathering-enriched deposits. Time will tell if new metallurgical approaches will be successful on an industrial scale and if these complex weathering-enriched zones can be economically processed at current (Table 1 and Fig. 3) and future REE prices over extended periods of time.

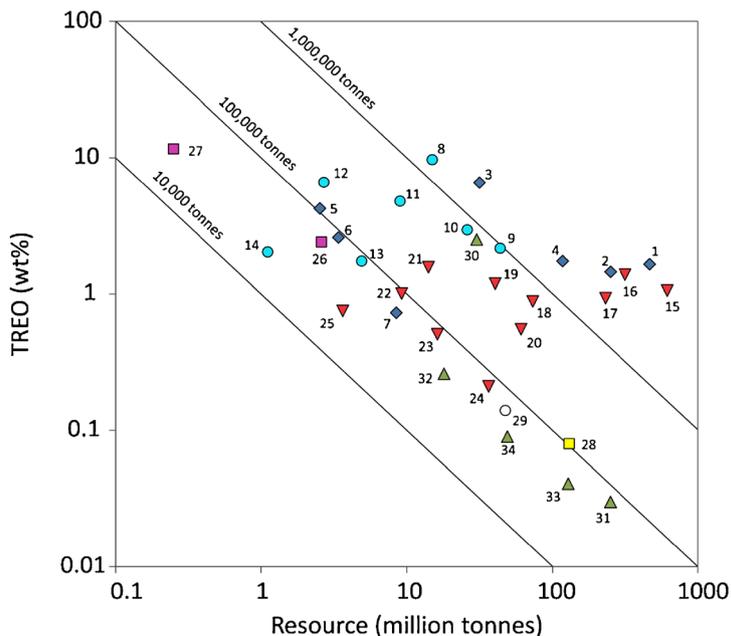
#### Ion adsorption clay deposits

“Ion adsorption clay deposits” are weathered crusts that may reach a depth of more than 20 m, developed by intense biochemical weathering in hot and humid (subtropical)

**Fig. 6** Typical chondrite-normalized patterns of REE for carbonatite-related deposits (Bayan Obo, Inner Mongolia, and Mountain Pass, CA), Peralkaline-hosted HREE deposits (Kipawa, Quebec) and ion adsorption clay deposits (Xinxiu, Southern China). Data from Saucier et al. (2013), Castor and Hendrick (2006), Yuan et al. (1992), and Bao and Zhao (2008)



**Fig. 7** Advanced REE exploration projects; grade (REO total)–tonnage plot; source: publicly available NI-43-101 technical reports or related press releases to March 2012. The diagonal lines provide convenient references for visual estimation of REO tonnages in the ground



- |                                      |                                |                          |
|--------------------------------------|--------------------------------|--------------------------|
| ◆ Carbonatite                        | 12 Araxá                       | ■ Monazite±apatite veins |
| 1 St Honoré                          | 13 Cummings Range              | 26 Hoidas Lake           |
| 2 Montviel (Core Zone)               | ▼ Peralkaline                  | 27 Steenkampskraal       |
| 3 Mountain Pass                      | 14 Xiluvo                      | ■ Ion adsorption clays   |
| 4 Eldor                              | 15 Kvanefjeld                  | 28 Tantalus              |
| 5 Kangankunde                        | 16 Nechalacho                  | ○ U by-product           |
| 6 Wigu Hill                          | 17 Strange Lake (B-Zone)       | 29 Eco Ridge             |
| 7 Clay-Howells                       | 18 Dubbo Zirconia Project      | ▲ Other/unknown          |
| ● Weathered Carbonatite              | 19 Two Tom                     | 30 Nolans Bore           |
| 8 Mount Weld Central Lanthanide Zone | 20 Norra Kärr                  | 31 Buckton               |
| 9 Zandkopsdrift                      | 21 Sarfartoq (ST1 Zone)        | 32 Kutessay II           |
| 10 Bear Lodge (Bull Hill Zone)       | 22 Foxtrot                     | 33 La Paz                |
| 11 Mount Weld Duncan                 | 23 Kipawa                      | 34 Canakli I             |
|                                      | 24 Hastings                    |                          |
|                                      | 25 Bokan (Dotson / I & L Zone) |                          |

climates. Most of the known examples are located in southern China and supply the bulk of the world's HREE requirements. Ion adsorption clay deposits in China overlie, in most cases, granitic rocks; however, the same deposit type may develop over gabbros, basalts, and other rock types (Ruan and Tian 2008). They are reddish in color and unconsolidated to partially consolidated (Wu et al. 1990; Bao and Zhao 2008). Grades are strongly dependent on the mineral and chemical composition of the protolith and vertical position within the weathered crust. Unconfirmed reports suggest that ion adsorption clay-containing reserves in China are dwindling. Similar deposits are located in areas with comparable climate and bedrock geology, such as Laos, northern Vietnam, Thailand (Sanematsu et al. 2009, 2011), and Madagascar.

Relative to monazite  $\pm$  apatite veins, or carbonatite- and peralkaline intrusion-related deposits, ion adsorption clay deposits are relatively low grade (Figs. 6 and 7), typically less than 0.5 wt% TREO. Under favorable conditions, where a very large proportion of REE are adsorbed to clay particles, even grades as low as 0.05 wt% REO are of economic interest. The distinction between REE adsorbed to clay particles and REE in weathering-resistant accessory and rock-forming minerals is paramount for correct evaluation of these deposits. Assuming the same total REE content and the same HREE/LREE ratio, a deposit having a higher proportion of clay-adsorbed REE to REE incorporated within a crystal lattice is more economically attractive. These deposits are economic because they are easy to mine and process. No blasting or crushing is required, and the liberation of clay-adsorbed REE may be achieved by in situ or heap leaching using dilute sodium chloride or ammonium sulfate solutions (Wu et al. 1990; Chi and Tian 2008). By western standards, these operations have a large environmental footprint. Many laterites that were historically evaluated as potential sources of industrial clays, as raw materials for alumina production, or ores of Ni or Al are being sampled as potential sources of HREO and Sc. Additionally, "red mud" (bauxite waste from the Bayer aluminum production process) contains significant concentrations of REE. An extraction pilot plant is being commissioned in Jamaica, known for red muds with the highest REE concentration (Jamaica Observer 2013).

#### Placers (heavy mineral sands)

Placer deposits are defined as accumulations of valuable heavy minerals liberated by weathering from primary ore deposits or nonmineralized rocks, transported, and concentrated mainly through processes involving water and wind. Placer classification is provided by Morison (1989), Garnett and Bassett (2005), and Levson (1995a, b). Placers and paleoplacers are sources of precious metals, uranium, zircon, titanium oxides, Ta- and Nb-bearing minerals, REE minerals, a variety of industrial minerals, and gemstones.

Zircon and REE minerals (primarily monazite and xenotime) were recovered as by-products of Ti-oxide placer operations in Australia until the late 1980s (O'Driscoll 1988). At that time, regulations associated with high concentrations of Th in placer monazite concentrates made bastnaesite and other REE-fluorocarbonates more appealing. Australia's resources alone are estimated to be on the order of 5.2 to 7.4 million t of monazite (Mernagh and Miezitis 2008; Miezitis and Hoatson 2012). Monazite can be concentrated by gravity, magnetic, and electrostatic separation.

Monazite contains about 50–78 wt% TREO. Xenotime [(YPO<sub>4</sub>)], also present in some deposits, contains 54–65 wt% TREO. The Th content of monazite is variable and in some cases may reach up to 30 wt%. Monazite-bearing heavy mineral deposits in India, Sri Lanka, Australia, and Egypt are described by Kumar (2011), Rupasinghe et al. (1983), Bhadra Chaudhuri and Newesely (1993), O'Driscoll (1988), and Hedrik and Waked (1989). Monazite concentrates from Australian mineral sands typically contain between 5 and 10 wt% Th; however, placer monazites from tin-bearing districts commonly have higher Eu and lower Th contents (Roseblum and Mossier 1983).

REE-bearing uranium deposits of the Blind River-Elliot Lake area (ON), discussed elsewhere, originated as paleoplacers (Roscoe 1996) and were significant sources of REE (Goode 2012).

#### Monazite $\pm$ apatite veins

REE-rich, small to medium tonnage veins may represent viable exploration targets even under 2013 REE market conditions (Fig. 3). These deposits are typically hosted by amphibolite- to granulite-grade metamorphic rocks. The REE ore mineralogy of individual veins is commonly distinct. Examples include Rareco's historic 300-m-long and 2-m-wide monazite-apatite-quartz Steenkampskraal vein (Fig. 5c) located in South Africa (Andreoli et al. 1994) and Hoidas-type deposits in Saskatchewan, Canada (Halpin 2010). The Steenkampskraal vein, which contacts or cuts a granitoid within a granulite-facies metamorphic terrane, was a historical source of Th and REE (Andreoli et al. 1994). Rareco estimated that the Steenkampskraal deposit may have 117,500 t of potentially recoverable resources remaining with an average grade of 16.74 wt% total REE (Dalgliesh et al. 2011). A more recent estimate for the mine area alone stands at 71,500 t at 23 wt% TREO and 95,800 t at 17 wt% TREO of indicated and inferred resource categories, respectively (McKechnie et al. 2012).

Several LREE-enriched veins, lenses, or dikes are known in Saskatchewan, Canada. They were emplaced in shear zones superimposed on deep-seated crustal discontinuities (Normand et al. 2009; Rogers 2011). The JAK Zone at Hoidas Lake is the best documented Canadian example. It

extends over 750 m along strike, to a depth of 150 m, and is 3 to 12 m wide (Normand et al. 2009; Rogers 2011). The JAK Zone contains a resource of 2,847,000 t grading approximately 2 wt% total REE (Great Western Minerals Group Ltd 2011a). REEs are contained largely in thorite and monazite inclusions within fluorapatite and in allanite (Ce). Monazite, bastnaesite, and chevkinite are minor constituents (Halpin 2010). The veins are enriched mainly in Ce and La and to lesser extent in Nd and other REE, but the chemical composition and mineralogy differ for each vein generation.

#### REE as by-product of uranium mining

Yttrium has historically been extracted as a by-product of uranium mining from uraniferous quartz pebble conglomerates of the Blind River-Elliot Lake deposits (ON). This district has produced 140,500 t of U from ores grading about 0.09 wt% U (Roscoe 1996). During processing of ores, large volumes of nearly U-free Th- and REE-containing liquor were produced. Rio Algom Mines and Denison Mines were able to recover REE by solvent extraction (Lendrum and McCreedy 1976; Lucas and Ritcey 1975; Goode 2012). The Eco Ridge deposit, located in the same area, is reported to contain indicated mineral resources of 14.3 million t at 0.048 %  $U_3O_8$  and 0.164 % TREO with inferred mineral resources totalling 33.1 million t at 0.043 %  $U_3O_8$  and 0.132 % TREO. It is an example of a currently active project belonging to this category (Cox et al. 2011b). Uranothorite, thorite, brannerite, coffinite, and unidentified uranium silicate are the main U- and HREE-bearing minerals at Eco Ridge while monazite is the main host to LREE (Cox et al. 2011b).

Several unconformity-related U deposits of the Athabasca basin in Canada, including Key Lake, Cigar Lake, and McArthur, contain significant concentrations of REE (Jefferson and Delaney 2007). Uranium ore minerals in these deposits contain up to 1.2 wt% total REE (Fayek and Kyser 1997) and substantial enrichment is reported along late oxidation–reduction fronts (Mercadier et al. 2011). At least, one major U-producing company was considering co-producing REE at the time of high REE prices (2010–2011). The REE–U association is also well documented in peralkaline granites at Bokan Mountain (USA) and the Mary Kathleen U-REE deposit characterized by a skarn mineral assemblage (Queensland) as described by Long et al. (2010) and Kwak and Abeyasinghe (1987), respectively.

#### Phosphate deposits

Phosphate deposits belong to two main categories: those that are associated with carbonatites or peralkaline intrusions and those that are of sedimentary origin. The geology of sedimentary phosphate deposits is covered by Slansky (1986), Trappe (1998), 1996), and Zhang et al. (2006) and summarized by

Simandl et al. (2012a). Sedimentary deposits are the most important source of phosphate and in some cases contain significant concentrations of lanthanides and Y (Altschuler et al. 1967; Slansky 1986; Cook 1972; Simandl et al. 2012a).

World phosphate rock production for 2009 was estimated at 158 million t (Jasinski 2010). An average phosphorite contains 461.7 ppm REE (Grosz et al. 1995), mostly contained in francolite (Fig. 5d) crystal structure. Assuming a typical phosphorite used in fertilizer manufacturing has the same REE content, the amount of phosphate rock mined annually could contain more than 70,000 t of REE. This opportunity should not be overlooked; however, there are also some truly exceptional REE-bearing phosphate deposits. A good example is the Melovoye deposit on the Mangyshlak Peninsula (Kazakhstan), where phosphatized bone detritus of fossil fish in pyrite-bearing clays contains P, REE, U, and Sc. The in situ U content of this deposit is 0.03–0.05 wt%; however, the bone detritus can be concentrated by washing, increasing U content two to three times (Abakimov 1995). Similarly, the TREO content of the washed bone detritus may reach 1 wt% (Kochenov and Zimovieff in Altschuler 1973).

Khibina, on the Kola Peninsula, is an excellent example of an igneous phosphate deposit (Kogarko 2012). Apatite from this locality is reported to contain approximately 1 % TREO (Zaitsev and Kogarko 2012). Commercial REE production from phosphate rock (Habashi 1985), most likely apatite concentrate, took place between 1965 and 1972 in Finland by Kemira Oy.

Recovery of REE from phosphate rocks as by-products of fertilizer production was considered by several companies in the 1960s and 1970s, but historic market conditions were unfavorable. REO prices approaching those of 2011 do justify reevaluation of their recoverability as co-products of phosphoric acid.

#### Peralkaline rock-related deposits

Alkaline intrusions are characterized by their content of feldspathoids, alkali amphiboles, and pyroxenes (Sørensen 1986). Based on molar ratios of  $[Na_2O + K_2O]$  relative to  $Al_2O_3$ , they are subdivided into metaluminous or peralkaline categories. In peralkaline intrusions:  $Na_2O + K_2O > Al_2O_3$  (Marks et al. 2011). Peralkaline intrusions are agpaiteic if their agpaiteic index  $((Na + K)/Al)$  is greater than 1 (Salvi and Williams-Jones 2004). Peralkaline intrusions, especially those of agpaiteic type, contain large deposits of Zr, Nb, Ta, Y, HREE, Th, and Be (Richardson and Birkett 1996c). Several of these deposits known in Canada (Simandl et al. 2012b), Greenland (Sørensen and Kalvig 2011), the Kola Peninsula (Kogarko 2012; Zaitsev and Kogarko 2012; Chakmouradian and Zaitsev 2012), and elsewhere have reached the advanced

exploration stage. The REE mineralization is mainly present within cumulate layers or within late pegmatite-textured rocks, but it may be also present in REE-enriched dikes, lenses, and veins cutting the intrusion.

The Lovozero massif in Russia, one of the largest apatitic intrusions in the world, is the only peralkaline intrusion-hosted REE deposit currently in production. This deposit contains loparite  $[(\text{Ce}, \text{Na}, \text{Ca})_2(\text{Ti}, \text{Nb})_2\text{O}_6]$  and is therefore preferentially enriched in LREE (Zaitsev and Kogarko 2012; Kogarko et al. 2002). Current annual rate of production is approximately 6,000 t of loparite concentrate grading 30–35 wt% TREO, 8–12 wt%  $\text{Nb}_2\text{O}_5$ , and 0.6–0.8 wt%  $\text{Ta}_2\text{O}_5$  (Zaitsev and Kogarko 2012). The mineralized zone also contains accessory apatite containing (5–6 wt% TREO) that is not currently recovered. Eudialyte is also present within the Lovozero intrusion. The metallurgy of the eudialyte zone has been investigated; however, it is not presently being mined.

Kvanefjeld, Kringleme, and Motzfeld are some of the better-known REE-Ta-Nb-Zr-bearing peralkaline intrusion-hosted deposits in Greenland (Sørensen and Kalvig 2011). The Nechalacho project near Thor Lake in the Northwest Territories (Williams-Jones 2010; Möller and Williams-Jones 2013), the Strange Lake Complex on the border of Quebec and Labrador (Kerr 2011; Boily and Williams-Jones 1994; Salvi and Williams-Jones 2004), and the Kipawa deposits of Quebec (Constantin and Fleury 2011; Saucier et al. 2013) are the three best-known Canadian examples.

The following Canadian examples illustrate the degree of variation in terms of available resource and mineralogy that may be expected when comparing peralkaline intrusion-hosted deposits. The Nechalacho REE-Zr-Nb-Ta deposit (formally the Lake zone of the Thor Lake project, NWT) has measured and indicated resources of 121.25 million t with grades of 1.5 wt% TREO, 0.25 wt% HREE, 2.56 wt%  $\text{ZrO}_2$ , 0.34 wt%  $\text{Nb}_2\text{O}_5$ , and 0.03 wt%  $\text{Ta}_2\text{O}_5$  and inferred resource of 183.37 million t grading 1.27 wt% TREO, 0.17 wt% HREE, 2.37 wt%  $\text{ZrO}_2$ , 0.33 wt%  $\text{Nb}_2\text{O}_5$ , and 0.02 wt%  $\text{Ta}_2\text{O}_5$  (Ciuculescu et al. 2013). The basal zone is enriched in HREE relative to the upper zone. The host rock is a foyaite, an aegirine-rich, medium to coarsely crystalline syenite containing euhedral K-feldspar in trachytoidal flow textures (Möller and Williams-Jones 2013). Allanite, monazite, bastnaesite, and synchysite are the main LREE-bearing minerals. Yttrium, HREE, and Ta are found principally in fergusonite; niobium in columbite; HREE and Zr in zircon; and Ga in biotite, chlorite, and feldspar of albitized feldspathic rocks (Cox et al. 2011a).

The Kipawa deposit, also known as the Sheffield deposit, located in southwestern Quebec (Canada), is an example of a mineralized peralkaline intrusion metamorphosed to upper amphibolite grade. Metamorphosed peralkaline and associated calc-silicate rocks and syenites strike NW–SE, dip shallowly SW, and have a striking radiometric signature. In the 1980s, a

Zr–REE zone 10–30 m wide was traced along strike for more than 1,300 m (Alan 1992). The main REE-bearing minerals are eudialyte, yttriotitanite  $[(\text{Ca}, \text{Y})\text{TiSiO}_5]$ , mosandrite group minerals  $[\text{Na}(\text{Na}, \text{Ca})_2(\text{Ca}, \text{Ce}, \text{Y})_4(\text{Ti}, \text{Nb}, \text{Zr})(\text{Si}_2\text{O}_7)_2(\text{O}, \text{F})_2\text{F}_3]$ , and britholite  $[(\text{Ce}, \text{Ca}, \text{Th}, \text{La}, \text{Nd})_5(\text{SiO}_4, \text{PO}_4)_3(\text{OH}, \text{F})]$ . Vlasovite  $[\text{Na}_2\text{ZrSi}_4\text{O}_{11}]$ , gittinsite  $[\text{CaZrSi}_2\text{O}_7]$ , and eudialyte were historically considered as a potential source of by-product Zr (Camus and Laferrière 2010); however, this is no longer the case (Saucier et al. 2013). Figure 5e, f shows spectacular examples of metamorphosed mineralization from the Kipawa deposit. Three vertically stacked co-planar mineralized zones have been recognized within the syenite based on the dominant ore mineral. They are referred to as eudialyte, mosandrite, and britholite zones. Vlasovite and its alteration derivative gittinsite are widespread throughout the deposit.

Peralkaline-related deposits are strongly enriched in HREE relative to carbonatites as illustrated by Kipawa (Fig. 6). They represent a main undeveloped resource of HREE. The mineralogy of these deposits is more complex than that of carbonatites. Historically, metallurgical requirements have prevented the development of peralkaline intrusion-hosted REE deposits, with the exception of the LREE-enriched, loparite-bearing deposit (described as nepheline-feldspar-aegirine pegmatite containing loparite and eudialyte; Roskill Information Services—unpublished data) at Lovozero. If metallurgical obstacles can be successfully overcome at reasonable cost, future development of one of these deposits may significantly reduce or eliminate world dependence on Chinese ion adsorption clays as the main source of HREE (Canadian Mining Journal 2013; Saucier et al. 2013; Quest Rare Minerals Ltd 2013).

#### REE-bearing IOCG deposits

The term “iron oxide copper gold deposit” (IOCG) is loosely defined. It covers a group of commonly sulfide-deficient deposits containing low-Ti magnetite and/or hematite of hydrothermal origin forming breccias, veins, disseminations, and massive lenses enriched in Cu, Au, Ag, U, P, Bi, Co, Nb, and REE (Corriveau 2007; Ray and Lefebure 2000; Williams et al. 2005). The best example showing significant REE enrichment is Olympic Dam (Australia). It contains the world's largest U resource (1.4 million t), the fourth largest copper resource (42.7 million t), and the fourth or fifth largest gold resource (55.1 million ounces) as reported by Corriveau (2007). The breccia zone of the deposit contains 3,000–5,000 ppm TREO and the central hematite-quartz zone is even richer (Reynolds 2000). Bastnaesite, fluorencite, and synchysite are the main REE-bearing minerals. Monazite, xenotime, and HREE-bearing zircon have also been reported. REE concentrations are positively correlated with the hematite content of the host rocks, and higher values occur in hematite breccias in the center of the deposit (Oreskes and Einaudi

1990). Kwajibo (Cu-REE-Mo-F-U-Au) and a few other occurrences in Quebec (Gauthier et al. 2004) are the best-known Canadian REE-enriched IOCG occurrences.

#### Pegmatite/granite

Granitic pegmatites (e.g., Tanco, Canada) are major sources of Ta, Li, Rb, Cs, Be, Sn, and industrial minerals (Sinclair 1996). Most rare metal pegmatites belong to the Li-Cs-Ta (LCT) family of pegmatites (Černý 1991a; b) and are derived from granitic sources. Chemical evolution through the Li-rich (LCT) pegmatite group is reflected by enrichment in volatiles, increased fractionation, and increased complexity of pegmatite zoning. The complexity of zoning also increases with distance from the granitic source (Trueman and Cerny 1982; London 2008).

The niobium-yttrium-fluorine (NYF) family of pegmatites (Černý 1991a; b) has higher REE contents than the LCT family and is also enriched in Be, Ti, Sr, and Zr. NYF pegmatites have an alkaline affinity and occur in the same intracontinental rift settings as peralkaline- and carbonatite-related mineralization (London 2008). Based on these characteristics, NYF pegmatites are probably genetically equivalent to late metasomatic phases of peralkaline intrusions characterized by pegmatitic textures, as described at Strange Lake (Quebec–Labrador, Canada). The Strange Lake deposit is commonly used as an example of a peralkaline intrusion-related deposit (Richardson and Birkett 1996c), although it has recently been described as a pegmatite (Linnen et al. 2012). Besides historic production required for research purposes in Europe, the Platt mine (WY, USA) is the only pegmatite that was mined primarily, and on an industrial scale, for its REE content. Approximately, 10,000 t of euxenite ore were recovered between 1956 and 1958 (Houston 1961) and shipped to Japan for processing. Similarly, a pegmatite deposit located 6 km east of Cooglegong Crossing (WA, Australia) was exploited on a small scale in 1913 and 1930 and produced approximately 2 t of gadolinite concentrate (Barrie 1965).

#### Skarns

Skarns are contact metamorphic or metasomatic zones formed by mass and chemical transfer between igneous and adjacent calcareous or dolomitic rocks. Typical skarn assemblages consist of pyroxene, garnet, idocrase, wollastonite, actinolite, magnetite, hematite, and epidote. Skarn deposits are sources of Au, base metals, Fe, W, and a variety of industrial minerals. Several skarns contain high concentrations of U and REEs (Kwak and Abeysinghe 1987; Lentz 1991; Oliver et al. 1999; Meinert et al. 2005). The REE-rich U deposit at the Mary Kathleen mine (Queensland) contained 6 million t grading 0.1 wt% U<sub>2</sub>O<sub>3</sub> and 2.6 wt% total REE (Kwak and Abeysinghe 1987). The total REE grades ran as high as

7.6 wt% (Cruikshank et al. 1980). U was found in uraninite, while REEs are present in allanite and to a much lesser extent in stillwellite and andradite (Kwak and Abeysinghe 1987). Recovery processes were investigated; however, REEs were not recovered.

#### Greisens and related veins

Greisens and veins typically form near the contacts between highly evolved peraluminous or metaluminous granitoids and country rock, in the proximity of stocks and batholith cupolas. Greisen deposits consist of cassiterite disseminations, veinlets, stockworks, lenses, pipes, and breccia with a gangue of quartz, mica, fluorite, and topaz. Veins are characterized by wolframite-series minerals and cassiterite (±scheelite, molybdenite, bismuthinite, base metal sulfides, tetrahedrite, arsenopyrite, stannite, native bismuth, fluorite, and beryl). Typical gangue minerals are quartz, muscovite, biotite, feldspar, tourmaline, topaz, pyrite, and chlorite (Cox and Bagby 1986; Reed 1986). Uranium, Th, and REE minerals are minor constituents of these deposits. It remains to be determined if some may contain REE in sufficient concentrations to be recovered as a co-product (David Trueman, personal communication 2012).

#### Sandstone-hosted xenotime deposits

Several xenotime-rich sandstone-hosted occurrences are reported within the Athabasca Group sedimentary rocks of Athabasca Basin (Harper 1987). REE mineralization forms lenses parallel to bedding within medium-grained, slightly foliated, hematite-bearing sandstone. The xenotime is interpreted to be of hydrothermal origin. Samples from the Douglas River project (SK) contain up to 4.8 % P<sub>2</sub>O<sub>5</sub>, 4.9 % Y, 9,100 ppm Dy, 2,990 ppm Er, 1,440 ppm Yb, and 2,150 ppm Tb (Great Western Minerals Group Ltd 2011b). Other known and related occurrences belonging to this category are located within the MAW REE zone that is characterized by breccia/conglomerate zones impregnated by tourmaline and silicified (MacDougall 1990; Quirt et al. 1991). Sandstone-hosted, xenotime-rich deposits are characterized by a relatively high HREE/LREE ratio.

#### Manganese nodules, REE-bearing ocean muds

REE-enriched manganese nodules (Piper 1974; Elderfield et al. 1981; Ohta et al. 1999; Hein et al. 2011; Zhang et al. 2012) and REE-bearing muds of the Pacific Ocean described by Kato et al. (2011) contain significant REE resources. Samples of these REE-bearing muds in the eastern South Pacific contain 1,000 to 2,230 ppm total REE (Kato et al. 2011). These types of deposits are of particular interest to governments of countries that do not have significant land-

based REE resources, such as Japan and some of the countries belonging to the European Union. The depths at which these resources are located represent technological challenges. Public sensitivities associated with the environmental impact of mining on the seafloor, international laws, a recent decline in REE prices (Fig. 3), and the high costs of specialized seabed mining equipment represent additional challenges (Agarwal et al. 2012; Bashir et al. 2012; Flentje et al. 2012).

#### Other deposit types

A review of compilation studies by governmental organizations worldwide, including the USA (Long et al. 2010), Australia (Hoatson et al. 2011), Canada (Simandl 2010; Simandl et al. 2012a, b, c), and Greenland (Sørensen and Kalvig 2011) clearly indicate that most REE-bearing deposits neatly fit into the deposit categories discussed above; however, new potential sources are in the process of being identified, and these new deposit types may not fit into these categories. For example, REEs are also present in significant concentrations in clay deposits that are being developed as sources of metallurgical-grade alumina. Orbite Aluminae Inc. plans to recover REE as a co-product of high purity alumina from its Grande-Vallée deposit in Canada (Levaque 2011; Doran et al. 2012).

The Athabasca oil sands in Canada represent an important source of petroleum. They also contain a significant low-grade resource of zircon and titanium-bearing minerals (Majid et al. 1988; Kaminsky et al. 2008). Progress is being reported toward the recovery of these minerals during bitumen processing. REO concentrations are not reported, but monazite is present in these deposits (Kaminsky 2008).

#### Technical, economic, and political considerations

Advanced projects outside of China show extreme variation in REO grade and deposit size. Figure 7 indicates available REE resources but ignores potential co-products such as Zr, Hf, Nb, P, F, U, etc. The recovery of these potential co-products needs to be considered when comparing individual projects. At least 16 of 25 REE projects worldwide are projected to be in production by 2016 (Watts 2012). Combined, they represent about 200,000 t of new REO production capacity outside of China. It is unlikely that all 16 will reach production stage.

The mineralogy of REE deposits, and by extension the relative cost-effectiveness of corresponding metallurgy, is extremely varied. Mineralogy needs to be considered during the early screening of exploration projects. As a rule of thumb, REE-bearing carbonates and fluorocarbonates are easy to deal with using conventional methods. The best example of an

operation that relies on bastnaesite  $[(\text{Ce}, \text{La})(\text{CO}_3)\text{F}]$  is the Mountain Pass mine (USA).

Deposits containing REE phosphates, mainly monazite group minerals  $[(\text{La}, \text{Ce}, \text{Nd}, \text{Th})\text{PO}_4]$ , have higher Th content. Radiation-related precautions may be required during mining, processing, transport of the concentrate, and waste disposal. Therefore, monazite-rich deposits are considered more difficult to permit than deposits consisting predominantly of REE-fluorocarbonates. Commercial nuclear reactors run on U but Th is seen by some as a safer and cleaner fuel. China, India, France, and Norway are pursuing Th-based nuclear fuel programs (Martin 2011). Commercialization of Th-based technology would make monazite an ideal REE ore mineral. Classical examples of past monazite-based operations are the Steenkampskraal vein (South Africa) and placer deposits in Australia.

Uranium ore minerals such as brannerite  $[(\text{U}, \text{Ca}, \text{Ce})(\text{Ti}, \text{Fe})_2\text{O}_6]$ , and to a lesser extent uraninite  $[\text{UO}_2]$  (including its massive form commonly referred to as pitchblende), and a variety of other U-bearing minerals may contain potentially recoverable REE. The brannerite-bearing uranium deposits of the Blind River–Elliot Lake area are excellent examples of successful historical co-production of U and REE (Goode 2012).

REE-bearing silicates (e.g., allanite,  $[(\text{Ce}, \text{Ca}, \text{Y})_2(\text{Al}, \text{Fe}^{3+})_3(\text{SiO}_4)_3(\text{OH})]$ ) are reported from some pegmatites, granites, gneisses, veins, and skarns.

Peralkaline intrusion-related deposits have been recognized as an REE resource for many years. An inability to commercially extract REE from eudialyte  $[\text{Na}_4(\text{Ca}, \text{Ce})_2(\text{Fe}^{2+}, \text{Mn}^{2+})\text{ZrSi}_8\text{O}_{22}(\text{OH}, \text{Cl})_2]$  and other complex and exotic minerals (with the exception of loparite  $[(\text{Ce}, \text{Na}, \text{Ca})_2(\text{Ti}, \text{Nb})_2\text{O}_6]$ ) historically prevented their development. Recent press releases from several junior exploration companies suggest that significant progress in REE extraction from eudialyte and other complex REE-bearing minerals has been achieved (Canadian Mining Journal 2013; Saucier et al. 2013; Quest Rare Minerals Ltd 2013). Mineralogical and metallurgical tests are fundamental for establishing relative development potential of individual peralkaline intrusion-related deposits.

REEs are currently considered as critical metals by the European Commission, USA and Japanese governments, other governmental and paragonovernmental organizations, and major industrial REE users. Continent- or country-specific efforts of these organizations to secure supplies of REE in their own jurisdiction (e.g., strategy to secure REE from Greenland; Pieterse 2013) may conceivably result in development of deposits with low to moderate technical/economic rankings relative to highly ranked deposits also located outside of China. While the impact of current policies of the Chinese government on REE markets can be reasonably predicted, such policies are subject to unexpected changes.

Political maneuvering aiming to guarantee the availability of REE at reasonable price within the European Economic Community, USA, and other countries adds an extra layer of complexity to REE market forecasting.

## Summary

Potential REE resources are present and plentiful on most continents and on the ocean floors. The global REE market is dominated by China, and REE prices are influenced by Chinese export quotas. Since 2011, the general trend in REE prices is downward; however, the prices are starting to stabilize. Several REE-bearing deposit types are potential sources of REE; however, as the prices of REE are stabilizing at levels well below the all-time highs reached during the summer of 2011, carbonatite-related deposits and high-grade REE-bearing veins are again becoming the preferred LREE development targets. Exploration for REE-bearing ion adsorption clay deposits outside of China and development of cost-effective metallurgical processes to extract REE from peralkaline intrusion-related deposits aim to eliminate world dependence on Chinese HREE exports. A combination of technical, environmental, economic, and political parameters will determine which deposit types (or specific deposits) outside of China will be developed during the next decade.

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