The global rare earth element exploration boom: An analysis of resources outside of China and discussion of development perspectives

Article *in* Resources Policy · June 2017

DOI: 10.1016/j.resourpol.2017.02.002

2 authors:

Holger Paulick
University of Oulu

Erika Machacek Faigen
Monash University (Australia)

Resources Policy 52 (2017) 134–153

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

The global rare earth element exploration boom: An analysis of resources outside of China and discussion of development perspectives

Holger Paulick[a], Erika Machacek[b,*]

[a] Oulu Mining School, University of Oulu, P.O. Box 8000, FI-90014, Finland
[b] Centre for Minerals and Materials, Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, 1350 Copenhagen, Denmark

ARTICLE INFO

Keywords:
Exploration
Rare earth element
Mineral resources
Investment
China
Greenland

ABSTRACT

This paper analyzes the mineral resource definitions from the exploration boom that followed the rare earth element (REE) price peak of 2011, and finds that

1. the delineated REE mineral resources outside of China reached a total of 98 Mt contained total rare earth oxides in 2015 with the majority located in Canada (38 Mt), Greenland (39 Mt) and Africa (10.3 Mt), representing a fivefold increase between 2010 (16.5 Mt combined) and 2015 (87.3 Mt combined).
2. a large portion of these resources contain REE bearing silicates as dominant ore mineral which have a higher heavy REE to light REE ratio than conventional carbonate-mineral REE resources.

The results highlight effective, stock market-financed exploration by junior companies and demonstrate REE resource availability outside of China. However, at current low prices, challenges to transform these resources from exploration to mining projects remain. These are tied to the up-scaling of beneficiation technologies for unconventional REE ore minerals and to raising investment for project implementation. In this context, we contend that the successful delineation of these REE resources provide abundant options for expansion and investment in the REE industry which are most likely harnessed by the dominant REE market player, China. Concerns about China's dominant role are therefore likely to persist.

1. Introduction

The group of elements commonly referred to as Rare Earth Elements (REE; here to include the lanthanides and yttrium) have recently moved into the spotlight for raw material policies and are characterized as "critical" for modern industrial applications (Massari and Ruberti, 2013; Buijs and Sievers, 2012; Barteková and Kemp, 2016). The demand for REE is highly variable and various combinations of elements are used in different intermediate industries such as phosphors (Eu, Y, Nd, Tb, Er, Gd), metal alloys (La, Ce, Pr, Nd, Y), catalysts (La, Ce), magnets (Nd, Pr, Dy, Sm) and ceramics and glass (Ce, La, Pr, Nd, Gd, Er, Ho). Substantial downstream processing and chemical separation of the mined REE bearing minerals is required before a final product, often a high-purity REE oxide (e.g., La_2O_3), can be sold to the manufacturing industry. Overall, the annual global production of Rare Earth Oxides (REO) increased from c. 60,000 t in 1994 to a peak of about 130,000 t in 2010 (Fig. 1; tonnes equals metric tons). Significant uncertainty prevails over production estimates, in particular with a view to the extent of illegal and undocumented production (Adamas Intelligence, 2016) and adherence to production and processing quota in China. However, these volumes are small compared to other mineral raw material such as base metals (e.g., Cu: 16 mio. tonnes for 2010 global production (USGS); or iron ore (about 3000 mio. t in 2012; Jenkin et al., 2015)). Consequently, the REE constitute a specialty metal sector where their processing typically involves customization to specifications of individual contract agreements.

Today, at least 85% of the supply of REE is derived from China (USGS, 2016b) where mining and processing has been concentrated as other large players started to leave the market in the late 1990s. This included the US-headquartered company Molycorp which closed the Mountain Pass mining operations in 2002 (Tse, 2011). Also, an increase in the share of beneficiated REE products (e.g., individual rare earth oxides and mixed rare earth compounds) used in domestic Chinese manufacturing is noticeable (e.g., for NdFeB and SmCo magnets for electrical equipment). Further, the vertical integration of mining, beneficiation, and manufacturing of intermediate components and the assemblage of final products such as smart phones, electronic products, wind turbines which contain REE-based parts, is observable in China.

---

* Corresponding author.
E-mail addresses: Holger.Paulick@oulu.fi (H. Paulick), em@geus.dk (E. Machacek).

http://dx.doi.org/10.1016/j.resourpol.2017.02.002
Received 23 September 2016; Received in revised form 7 February 2017; Accepted 7 February 2017

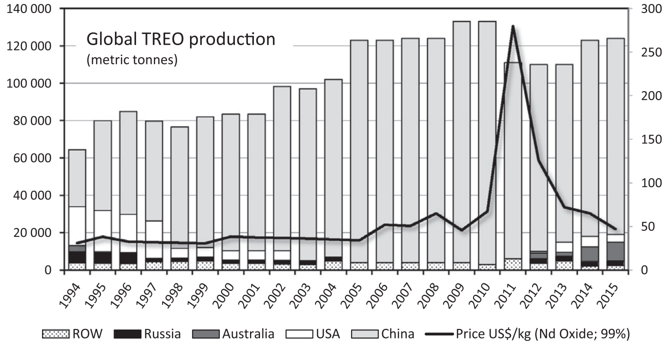


Fig. 1. Global annual production of Rare Earth Oxides (REO). Production has doubled from 1994 (65,000 t) to about 130,000 t in 2010, and about 120,000 t (with an official Chinese domestic production quota of 105,000 t, and production outside Chine) in recent years. During the same time, the supply market has changed with Chinese producers providing more that 95% of the market share from about 2003–2011. Following the price peak for all REO in 2011 (here, price data for Nd oxide, 99% is shown) the supply side has somewhat begun to diversify again with operations in Australia and the USA. Production data from USGS. Price data from USGS 1994–2005) and BGR (Price monitor, 2006–2015; FOB China); annual average prices rebased to 2013 dollar values.

Following a period of a fairly stable REE price regime (Fig. 1), prices rose in late 2010 reaching a peak in 2011 and arguably prompted the recent REE exploration boom. This response reflects also the uncertainties related to Chinese industrial policies including on REE mining and processing, export quota and value-added duties (Mancheri, 2015; Wübbeke, 2013). Subsequently, global REE exploration activities surged and by 2012 more than 200 specialized exploration companies were pursuing prospects of discovering and developing REE resources outside of China (Hatch, 2012).

Clearly, sudden rises in exploration and investment in junior exploration companies are not unique features of the REE market. Often, rises in raw material commodity prices (e.g., for gold, iron or copper) stimulate exploration in anticipation of substantial returns on investment from newly discovered resources. Nonetheless, the case of REE is distinct because any potential mine development arising from the exploration activities will have to compete with the REE mining and production plans of China, which is holding a dominant market-share of the global REE value chain.

It is important to emphasize that all 17 REE are commonly enriched together by geological processes in particular REE-bearing minerals. Therefore, it is not possible to selectively target just one specific element of the REE family for mining. In addition, the relative proportions of REE vary substantially according to the specific geochemical conditions of mineralization, the type of REE-bearing minerals present and the differences in general crustal abundance (ranging from 64 ppm for La to < 1 ppm for REE such as Eu, Tb, and Lu; Taylor and McClennan, 1985). In general terms, light REE (La, Ce, Pr, Nd, Sm; LREE) are substantially more abundant in REE deposits exploited today than the heavy REE (Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y; HREE). As a consequence, production volumes for Ce, La or Nd are in the order of tens of thousand tonnes whereas production volumes for most HREE are only a fraction thereof (i.e., typically < 1000 t; Table 1). The long term price developments (2007–2015) show that all REE reached a price peak in 2011 related to perceived imminent resource scarcity (Campbell, 2014). The deterioration of La and Ce prices during recent years indicates a significant oversupply of these REE. Furthermore, the development of LED lighting as a replacement for phosphors has reduced the demand for some HREE such as Eu whereas the relative robustness of Dy and Nd prices are reflections of the continued high demand from the magnet industry (Adamas Intelligence, 2016).

Overall, it is apparent that the demand pattern for REE has changed in recent years (Alonso et al., 2012; Schüler et al., 2011; Hoenderdaal et al., 2013) with a tilt towards higher use of HREE as functional materials, e.g. in permanent magnets that are used in high tech electronic hardware and "green-tech" applications. This has been conclusively illustrated in a comparison of REE end uses in 1995 and 2007 by Du and Graedel (2013). It is also likely that the shift from fossil energy fuels to renewable energy sources will further nurture this pattern as direct drive wind turbines utilize REE magnets, and (plug-in) hybrid/electrical vehicles LREE in batteries, and REE-magnets in motors. Simultaneously, demand for electronic consumer goods is likely to increase. With current supply of REE biased towards LREE, and mismatching industrial demand, the "balance problem" remains (Binnemans and Jones, 2015; Binnemans et al., 2013; Falconnet, 1985). Increases in demand for HREE might challenge supply, as (1) total REE consumption is likely to increase, and (2) the "spectrum" of REE use will turn increasingly towards HREE. The challenge is thus to explore for and develop additional resources that comply with these demand parameters, while also augmenting REE recycling rates.

This paper investigates how recently delineated REE resources are positioned with regard to this issue by examining the relationship between main types of REE-bearing mineral in these deposits and the characteristics of LREE/HREE ratios. Furthermore, we address the effectiveness of recent global REE exploration initiatives and the changes of "in-ground" resource values from 2011 to 2015. Changes in market capitalization of the companies that carried out the resource definition activities are investigated to elaborate on the likelihood of obtaining financing for mine development.

In an effort to place the results of the REE exploration boom in a global context we discuss the specific conditions of the REE market and the dominant role of China, which, in our opinion, is likely to prevail in the foreseeable future, in contrast to a scenario by Schlinkert and van den Boogaart (2015) that suggests an oligopoly might form. In particular, it appears that current low share prices of the stock market-listed REE exploration companies represent excellent opportunities to acquire the explored deposits and to secure the supply of REE-bearing minerals to existing beneficiation facilities. In other words, if this scenario was to materialize, the results of the global REE exploration boom could in fact contribute to the further dominant role of China in the REE industry.

1.1. Investigating the global REE exploration boom – General considerations

In this paper we examine the results of the short-lived, but highly successful global REE exploration boom from 2010 to 2014 that yielded outstanding results in terms of newly defined REE resources outside of China (mainly in Canada, Australia, Africa, and Greenland). In particular, we examine the types of mineral resources defined since REE can be hosted is a variety of REE-bearing mineral types (e.g, Chakhmouradian and Wall, 2012; Wall, 2104). Today, REE-bearing carbonates (bastnäsite) and phosphates (monazite, xenotime) are commercially processed whereas the processing technologies for REE-bearing silicates require additional R&D investment to be commercialized. Furthermore, we investigate the financial status of REE exploration companies that were successful in publishing REE resource estimates. Changes in the perceived market value of these discoveries can be characterized by comparing share price and market capitalization values using data from the start (early 2011) and approximate end (early 2015) of the exploration boom.

In general, resource exploration is an important part of the mineral raw material value chain and commonly driven by price incentives when increasing demand outpaces supply from existing mines and secondary sources (e.g. recycling). Furthermore, access to resources might be artificially constrained. For example, regulatory changes regarding export quota in the Chinese REE market served as signal for a potential, imminent supply risk, arguably enhanced by concerns

Table 1
Production volumes (2010) and price developments (2007–2015) for individual REE oxides.

	Oxides of:		Production (2010)		Prices (US$/kg)3)								
			%	tonnes1)	2007	2008	2009	2010	2011	2012	2013	2014	2015
L	Cerium	Ce	42.6	55.000	40	30	30	30	100	28	8	5	2
R	Lanthanum	La	25.4	33.000	30	30	38	38	100	58	20	5	3
E	Neodymium	Nd	17.2	22.000	45	42	63	63	270	124	72	65	47
E	Praseodymium	Pr	5.5	7.200	60	38	60	60	225	118	85	99	67
H	Yttrium	Y	4.4	5.700	50	44	50	50	165	110	26	15	7
R	Dysprosium	Dy	0.7	910	150	170	310	310	1600	1203	557	373	271
E	Europium	Eu	0.2	260	1000	1600	1400	1400	3300	2610	1102	771	269
E	Terbium	Tb	0.2	260	800	900	1400	1400	2750	2035	925	657	547

Notes: Production in % from Roskill (2011). nd: no data 1): Calculated based on a value of 130.000 t total annual production (source: USGS). Combined production levels for Sm, Gd, Ho, Er, Tm, Yb and Lu in 2010 are: 5.000 t (3.8%). 2): Annual average prices for REE oxides (99%). Sources: USGS (2007–2011) and German Raw Material Agency ("Deutsche Rohstoffagentur") (2012–2015).

over the use of REE by China in territorial claims with Japan, and consequently resulted in parabolic price increases. In this situation, stockpiling by manufacturers dependent on REE-based intermediate products was likely the main driving force behind the price surge. However, some scholars argue that at least a certain element of speculative investment has also been a factor in the escalating price dynamics (Campbell, 2014).

This chain of events implied a potential supply risk, heightened awareness of mineral raw material criticality, and fostered research initiatives and interest in REE supply from sources outside of China (Barteková and Kemp, 2016). The re-opening of the previously active REE mine at Mountain Pass (USA) and of Mt Weld (Australia) appeared as a viable option. However, potential higher financial gains are to be realized by early investments in REE exploration projects.

Mineral exploration is generally carried out by mining companies which invest revenues from producing mines, both strategically and as a means to replace exploited reserves. Furthermore, an abundance of specialized junior exploration companies fund their activities entirely from private or institutional investments. This business area is commonly associated with "high-risk/high reward" scenarios (Majury, 2013). In fact, a majority of junior exploration company projects fail to commercialize. For example, an investigation of the Australian junior exploration sector demonstrated that only about 10% of the companies succeeded in establishing a long-term mining operation between 2004 and 2014 (Schodde, 2015). Nonetheless, the prospect of extraordinary profits that may materialize if a valuable and feasible resource is discovered represents a substantial incentive for investment.

The mineral sector therefore presents opportunities for long term investments in form of anticipated dividends when mining operations generate profits, and opportunities for short term profits for speculators dealing with traded commodities or with shares of the involved companies. For example, some investors in physical or ETF-traded gold pursue profits by predicting the direction of price movements and may also invest in junior exploration companies when there is a perceived upward potential in share price.

With regard to the REE market, it is remarkable how efficient rising REE prices created incentives to invest in exploration, fueling a global exploration boom. Over a timeframe of just four years the defined REE mineral resources outside of China have more than doubled from 40 Mt (2011; USGS) to 98 Mt (TMR, 2016). This result is mainly attributable to the activities of junior exploration companies in Australia, Canada, Greenland and Africa.

Nonetheless, multiple layers of complications arise as to whether these mineral resources will eventually be converted to exploitable mineral reserves. Some of these issues relate to technological challenges (e.g., R & D required to commercialize processing methods for non-traditional REE-bearing minerals) whereas other concerns relate to the economic and geopolitical particularities of the REE market. These subjects are discussed based on the data examined in this paper.

1.2. The REE industry – Production and prices

Besides mining, processing and manufacturing activities based on REE in China, two larger REE mining operations were developed shortly after the 2011 REE price peak: in the USA with the Mountain Pass mine by Molycorp, and in Australia with the Mount Weld mine by Lynas (Machacek and Fold, 2014). In late 2015, the Mountain Pass operations were returned to care and maintenance status. Significantly smaller mining operations are in India, Malaysia, Brazil and Vietnam, where REE bearing minerals are a by-product of mineral sand mining mainly targeted at rutile and zircon. Furthermore, REE are a by-product of apatite and niobium mining and processing in Russia. Overall, the total of REE mined outside of China in 2015 amounted to about 16,000 t (China: 105,000 t; USGS, 2016a).

Substantial differences in production volumes for the different REE and general price levels can be noted (Table 1). These range from the "low value-high volume" LREE to the "high value-low volume" HREE. In particular, more than 85% of the REE oxides produced are represented by three LREE, namely Ce (43%); La (25%) and Nd (17%; Roskill, 2011; Table 1). This represented a share of 118,000 t of global production in 2010 (total: 130,000 t; USGS, 2011). In contrast, HREE such as Eu, Gd, Tb, Dy and Er accounted for less than 5% of production (total: 3 500 tons). The main importers of Rare Earth Oxide (REO) products from China are Japan, South Korea, the USA and the European Union whereas other industrialized countries mainly import REE-bearing components used in manufacturing (e.g., electronic components used in the automotive industry).

The REE price peak conditions of 2010–2012 have not prevailed (Fig. 1, Table 1). For some REE, the current prices are similar to "pre-peak" conditions, e.g., Nd (2007: 45 USD/kg, 2015: 47 USD/kg) and Pr (2007: 60 USD/kg, 2015: 67 USD/kg). In contrast, other REE have lost substantial value, such as Ce (2007: 40 USD/kg, 2015: 2 USD/kg), La (2007: 30 USD/kg, 2015: 3 USD/kg), and Y (2007: 50 USD/kg, 2015: 7 USD/kg). The downturn in REE prices might be indicative of manufacturers' success in reducing REE usage in their applications and/or the development of substitutions. This would be consistent with the stabilization of REE production levels at around 110,000–120,000 t/yr (2011–2015) which is c. 10,000–20,000 t below peak volumes produced in 2009 and 2010 (Fig. 1).

1.3. The spectrum of REE deposits and REE bearing minerals

The REE are concentrated in different geological environments and, on a first order scale, deposits can be classified as related to processes within the Earth's crust ("endogenous deposits") as opposed to deposits that are formed during weathering and/or sedimentary processes ("exogenous deposits"). Geological features of the various REE deposits have been recently summarized in several publications (e.g., Chakhnouradian and Wall, 2012; Wall, 2014; Jaireth et al., 2014; Linnen et al., 2014; Weng et al., 2015, Goodenough et al., 2016). However, it is important to take note that certain REE ore minerals are associated with particular deposit types, e.g., weathering resistant REE phosphates (xenotime, monazite) can be concentrated in mineral sands.

Traditionally, the bulk of REE have been produced from mines containing a particular type of REE flourocarbonate, namely bastnäsite, which is strongly enriched in LREE compared to HREE (Chakhmouradian and Wall, 2012). Hence, HREE enriched xenotime and monazite can be an attractive by-product of mineral sand operations providing supplementary supply to the high value/low volume segment of the REE spectrum. Furthermore, ion-adsorption clay deposits are being exploited in southern China where solvent extraction techniques can be applied to yield a HREE rich solution. However, in-situ leaching can be associated with significant environmental damage in particular when carried out under unregulated or illegal circumstances (Packey and Kingsnorth, 2016).

In terms of the processing required to generate individual REE oxides from the mined REE bearing minerals, there are well established industrial-scale methods for bastnäsite, xenotime and monazite that have been applied and developed over several decades (Jordens et al., 2013). These technologies and know-how concentrated in China, while the REE processing industry declined in the USA and Europe in the 1990s. Integrating the processing chains for the beneficiation of REE bearing minerals has been part of the business strategy of Molycorp and Lynas.

There are numerous other minerals that contain significant concentrations of REE and many of the deposits targeted by junior exploration companies contain these "nontraditional" REE bearing minerals. These include various carbonates and fluorocarbonates, phosphates, oxides and silicates. In particular, silicates are an important group representing a REE source that is associated with specific magmatic rocks ("alkaline intrusions"). Commonly, these REE bearing silicate minerals (such as e.g., eudialyte, steenstrupine and allanite) show elevated concentrations of HREE compared to (fluoro)carbonates (Linnen et al., 2014; Kanazawa and Kamitani, 2006). Provided that appropriate beneficiation and processing technologies can be established on an industrial scale, there is a large potential for new types of REE bearing minerals to contribute to the future REE market.

2. Data and methods

In this study, several data sources are used to examine parameters such as resource size, grade, mineralogy (i.e., type of REE bearing minerals in the resource), and value, in order to characterize the outcome of the global REE exploration boom. We draw on published REE resource figures[1] compiled by Technology Metals Research (TMR), a recently established organization that maintains a systematic record of publically reported REE resources (TMR, 2015). This "TMR Advanced Rare-Earth Projects Index (TMR Index)" lists 49 REE projects with a total of 58 individually delineated REE resources (as of June 2015). Specifying resource tonnage, grade and the concentrations of individual REO (see Appendix, Table A1). Hence, it is possible to calculate the content of each individual REO in tonnes for each resource. The sum of these is the total REO (TREO) content of the project, however, subtotals of heavy REO (HREO) and light REO (LREO) provide some interesting insights with regard to the characteristics of the projects (Table A2). Note that this undebased approach ignores potential complications related to mineral processing, recovery rates or the fact that only a portion of the resources will eventually be classified as reserves during more in-depth feasibility analyses. Overall, it is an important first order observation from the TMR Index data that a substantial number of the projects, and in fact >80% of the TREO contained in the resources, are in Greenland, Canada and Africa.

For a comparison of the current status of defined REE resources with the situation before the REE exploration boom we use 2010 data for global REE resources. For such a purpose, the archive of the United States Geological Survey (USGS) is a valuable source with its annual reports on national and global mining activities for a large range of commodities (e.g., USGS, 2011, 2016a, 2016b). The information commonly includes a mixture of code-compliant resource estimates, historical data, mineral intelligence and geological estimates depending on jurisdiction and data availability. For 2010, the USGS reports the following resource figures for TREO (USGS, 2011): USA: 13 Mt; Australia: 1.6 Mt; Brazil: 0.05 Mt; China: 55 Mt; Russia (Commonwealth of Independent States): 19 Mt; India: 3.1 Mt; Malaysia: 0.03 Mt; other countries: 22 Mt for a global total of 110 Mt. Since data for Greenland, Canada and Africa have been included in the category "other countries" by USGS (2011) we complement the data with figures published by Polinares (2012) for these jurisdictions: Greenland: 10.4 Mt, Canada: 3.7 Mt, and Africa: 2.4 Mt.

The prices for individual REO have been published in the USGS in the annual "Minerals Yearbook" series. However, this practice was discontinued with the last annual average price information for REO from this source available for 2012. Hence, price information from 2012 onwards was sourced from the German Federal Institute for Geosciences and Natural Resources ("Bundesanstalt für Geowissenschaften und Rohstoffe") using the "Preismonitor" monthly reports (BGR, 2016).

By combining the project specific information regarding the content of individual REO it is possible to calculate the "in ground value" for each of the listed resources and determine changes related to price fluctuation. This value is determined applying the following calculation:

$IGV_{(project,\ year)}$=X(La_2O_3, project)*P(La_2O_3, year)+X(CeO_2, project)*P(CeO_2, year)+X(Pr_6O_{11}, project)*P(Pr_6O_{11}, year)+X(Nd_2O_3, project)*P(Nd_2O_3, year)+X(Sm_2O_3, project)*P(Sm_2O_3, year)+X(Eu_2O_3, project)*P(Eu_2O_3, year)+X(Gd_2O_3, project)*P(Gd_2O_3, year)+X(Tb_4O_7, project)*P(Tb_4O_7, year)+X(Dy_2O_3, project)*P(Dy_2O_3, year)+X(Ho_2O_3, project)P(Ho_2O_3, year)+X(Er_2O_3, project)*P(Er_2O_3, year)+X(Tm_2O_3, project)*P(Tm_2O_3, year)+X(Yb_2O_3, project)*P(Yb_2O_3, year)+X(Lu_2O_3, project)*P(Lu_2O_3, year)+X(Y_2O_3, project)*P(Y_2O_3, year)

IVG: In-ground value for a specific project and year.

X: Content of an individual REO in tonnes in the resource (undebased)

P: Average annual price per tonne of a specific REO (Table 1). Note that prices for Gd_2O_3, Ho_2O_3, Tm_2O_3 and Lu_2O_3 are not publically available. Hence, the IGV calculated excludes contributions from these elements.

In this paper we use the resource data in combination with the annual average prices for 2011 and 2015 to calculate IGV(project, 2011) and IGV(project, 2015) in order to examine the - real or perceived - impact of changes in supply/demand conditions from the peak price environment to the currently prevailing lower price conditions.

In order to compare the resources according to their relative value, we use the IGV data for 2011 and 2015 and normalize it to one kilogram of contained TREO. This parameter is commonly referred to as the "basket prize". It typically returns higher numbers for resources characterized by elevated proportions of HREE. It must be cautioned

---

[1] Disclosure requirements for public companies traded on the stock markets ensure that their activities and status of projects are reported. For mineral exploration companies there are particular codes for publishing resource and reserve calculations (e.g., JORC, NI43-101, PERC, SAMCODE (SAMREC, SAMVAL, SAMOG) etc.), since these are of fundamental importance with regard to the potential value of the mineral deposits held in their portfolio.

that this parameter has minor bearing for judging the profitability of an eventual mine development since this depends strongly on the expected operation costs (Bogner, 2015).

Furthermore, an important parameter pertaining to the value of projects listed in the TMR Index is the value of an average tonne of the resource (i.e., IGV/resource tonnage) since this is controlled by both, the average TREO concentration and the spectrum of REE contained. A project with a large resource tonnage may have an impressive IGV but low grade and therefore face challenges when production costs per tonne of ore are calculated during the feasibility stage. However, relatively high concentrations of HREO may counterbalance this effect.

Importantly, we investigate relationships between deposit size (i.e., tonnage of the resource), average TREO grade and the differences in REE spectrum (i.e., LREE/HREE ratio) of the resources by taking into account the main type of REE bearing minerals involved. Based on company reporting regarding the types of REE bearing minerals of their projects, the resources are grouped into carbonate-, phosphate-, or silicate-dominated REE deposits.

To characterize the resource value as perceived and reflected on the stock market we also examine changes in market capitalization of the publically listed companies holding the rights to the delineated resources with data from 2011 and 2015. Data for market capitalization (i.e., share price multiplied by shares outstanding) for spring 2015 was obtained from Bloomberg (2015). From the same source, the peak share prices for the companies in spring 2011 have been obtained. For data regarding shares outstanding in 2011, company web sites and stock market filing systems for the Canadian and Australian stock exchange (Sedar, 2015). This time series comparison served as a basis for estimating the order of magnitude of financing made available to REE exploration companies to fund exploration activities.

3. Effects of the exploration boom on options for REE supply

In general, the delineation of raw material resources in the mining industry is a dynamic process which is dependent on commodity price developments, justifying the required investments in exploration. Also, what is regarded as a body of rock of sufficient size and ore mineral concentration with the potential to support a profitable mining operation is dependent on factors including mining engineering technology, operating and investment costs as well as legal, fiscal and permitting frameworks. Therefore, it must be highlighted that figures on mineral resource content are constantly evolving. Furthermore, it is important to note the difference in the terms "resource" and "reserve" in reporting codes such as JORC (2012; Australia) and NI 43–101 (North America) that are designed to regulate the communication of companies' exploration results to the stock market. For resources, the main factor is the degree of geological knowledge whereas economic considerations are in the focus as parts of the resource are transferred into reserves. Furthermore, it is noteworthy that companies operating outside of stock market regulations do not need to comply in the same way to these rules.

3.1. Increase in reported global REE resources outside of China

The recent REE exploration boom led to the discovery and delineation of REE resources particularly in Greenland, Canada, Africa, and Australia (Fig. 2). In detail, there are now data which characterize 58 individual resources from 49 REE deposits (TMR, 2015, detailed resource data, geological description and IGV data in the Appendix: Tables A1 and A2). In particular, the data for projects in Greenland, Canada and Africa clearly show the effect of the intensified exploration efforts. Here, reported TREO contents of the resources are: 39 Mt in Greenland (3 projects), 38 Mt in Canada (15 projects) and 10.3 Mt in Africa (11 projects). The *fivefold* increase of TREO resources in these jurisdictions from 2010 (16.5 Mt combined) to 2015 (87.3 Mt combined) is remarkable. This significant result has been realized in a short time frame and demonstrates the effectiveness of the stock market investment-funded junior exploration sector of the mining industry. On a smaller scale, a similar development can be observed for Australia. Here, 8 individual projects yield a combined TREO value of 4.3 Mt whereas the estimate for resources in 2010 was 1.6 Mt (USGS, 2011).

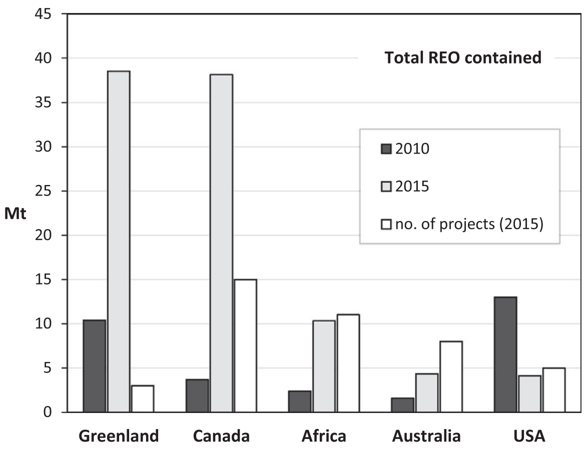


Fig. 2. Development of total REO resources in the principal jurisdictions where REE exploration has been concentrated during the exploration boom. The starting situation is characterized by data for 2010 (sources: USGS (2011) and Polinares (2012); see Section 2: Data sources and methods). The data for 2015 is shown as compiled in TMR (2015). Clearly, exploration activities have substantially increased the known REE resources in Greenland, Canada and Africa whereas the increase in Australia is comparatively modest. The apparent decrease in REE resources in the USA is most likely due to the reclassification of historic data from the Mountain Pass mine according to NI43-101 code compliant reporting required by stock market regulations today. Note that the reported REO resources in Greenland are strongly concentrated (3 individual projects with two of them Kringlerne and Kvanefjeld in immediate proximity in SW Greenland) whereas the total resources in Canada, Africa, Australia and USA are more diversely distributed (Tables A1 and A2).

The development for other parts of the world where REE exploration has been conducted is less clear due to uncertainties in 2010 data. For example, the TMR Index (2015) lists 5 REE projects in the USA (including Mountain Pass) for a total of 4.1 Mt whereas the estimate for 2010 is 13 Mt (USGS, 2011). This might be due to the reclassification of historic resources at Mountain Pass using the more stringent requirement of NI43-101 reporting. Furthermore, TMR (2015) reports resources in Sweden, Germany, Kazakhstan, Turkey, and Brazil (total of 2.5 Mt TREO).

Overall, the resources defined during the exploration boom contain 98 Mt of TREO. Furthermore, the US Geological Survey estimates TREO resources of 55 Mt and 12 Mt, in China and Russia, respectively (USGS, 2016a). In a simplistic view, these 165 Mt of global TREO resources would be sufficient to account for several hundreds of years of REE demand at current consumption rates (i.e., 120,000 t in 2015) even assuming recovery rates of 50–70%. In addition, REE resource in mineral sand deposits, where REE-bearing minerals are recovered as by-products of heavy mineral (rutile, ilmenite, zircon) mining, are a source of supply from India, South Africa, Malaysia, Thailand and Vietnam. Hence, the data demonstrate ample geological endowment of REE on a global scale and in particular outside of China.

3.2. Tonnage and grade

The tonnage and grade of mineral resources are first order parameters used to compare mineral deposits and judge their potential for successful (i.e., profitable) operation. As a rule of thumb, it can be expected that lower grade deposits will have higher operating costs (OPEX) per volume unit extracted compared to resource with higher grades. The resource tonnage may be regarded as the limiting factor that determines for how many years the mine might be in operation

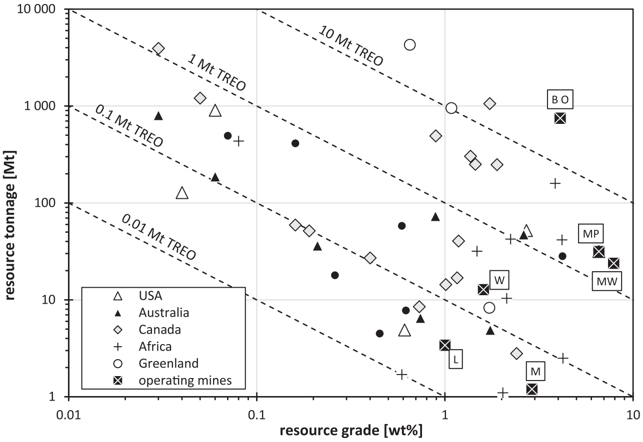


Fig. 3. Tonnage and grade characteristics of REE projects defined outside of China during the recent exploration boom compared to operating mines (status 2015). Abbreviations for data points from operating mines (from Wall (2014)): BO: Bayan Obo (China), L: Lovozero (Russia), M: Maoniuping (China), MP: Mountain Pass (USA), MW: Mount Weld (Australia), W: Weishan (China). The compilation by Wall (2014) lists also Dalucao (China), Khibiny (Russia) and Sareco (Kazakhstan) as operating REE mines, however, grade information for these operations are not documented. Note that the Steenskampskrall project (South Africa, Tables A1 and A2) has a resource grade of 14 wt% TREO but a relatively small tonnage (0.7 Mt), hence it is plotting outside of this diagram. Also, the Wigu Hill Twiga deposit (Tanzania) is outside of this diagram (0.5 Mt and 5.27 wt% TREO grade).

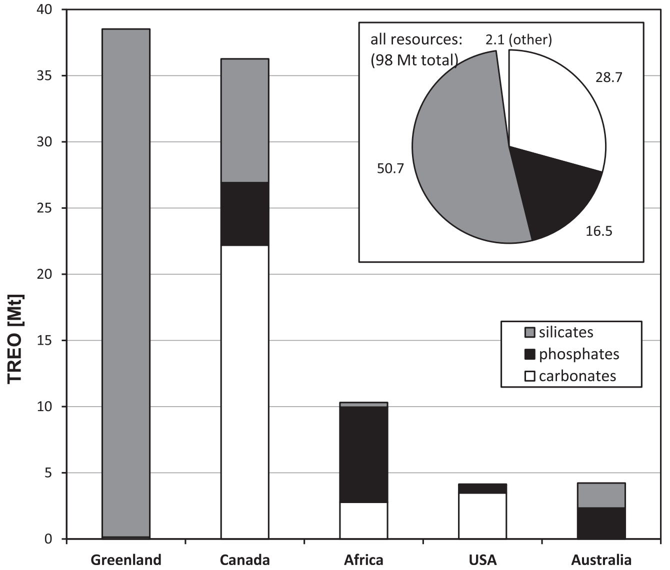


Fig. 4. The REE resources defined during the exploration boom consist of a variety of REE-bearing ore minerals. On a first order, these can be differentiated into silicates, phosphates and carbonates (see Table A2). About half of the REE contained in these resources is hosted in silicates (50.7 Mt; see inset pie chart). In terms of regional distribution, it is apparent that the large resources in Greenland are dominated by REE deposits with REE-bearing silicate phases which are also important in Canada. However, Canada also has a large proportion of resources dominated by carbonate REE minerals which are also common in Africa and the USA. Resources dominated by REE-bearing phosphates are common in Australia, Africa and Canada.

(life of mine). This is also a critical parameter since up front capital expenditures (CAPEX) are required to open a mine, and have to be recuperated during operation before a return on investment might be generated.

In Fig. 3 the tonnage and grade data for the resources defined during the exploration boom are shown jointly with corresponding data for operating mines in 2015. It is apparent that most of the exploration projects overlap with the current mines in terms of tonnage, however, a substantial share appears to be of insufficient low grade to compete with current suppliers (i.e., below 1 wt% TREO). The most prominent peer in the REE mining market are the mining operations at Bayan Obo (China) which also produce iron ore. This deposit has a resource of 750 Mt at an average grade of 4.1% TREO (Wall, 2014) which represents a benchmark “tier 1” REE deposit on a global scale (Fig. 3). Apparently, the global exploration boom did not succeed in finding new resource of such size and grade (Table A2). However, similar total REO endowment (> 10 Mt contained TREO) has been found in Greenland (Kringlerne and Kvanefjeld) and Canada (Niobec) but at significantly lower average grades (0.65–1.7 wt%). Two of the REE deposits in the database with relatively high grades (6.6 wt% at Mountain Pass, USA and 7.9 wt% at Mount Weld, Australia) did go into production following the REE price peak in 2011. The open pit REE mines at Weishan (China) and Maoniuping (China) are operating at considerable lower grades (1.6 wt% and 2.9 wt%, respectively). Furthermore, at Lovozero (Russia) REE-bearing minerals are recovered as a by-product of mining targeted at Niobium, thus representing a special case.

Overall, it could be assumed that deposits in the 2–4 wt% grade range may be in a position to add to global REE production at competitive operation costs. Among the recently defined resources 10 projects possess grades in this range, 6 of them are located in Africa. However, since there are considerable differences in the value of particular REO it is of great importance to consider the REE spectrum of the individual deposits in more detail. Clearly, a resource with a low TREO grade but a high proportion of valuable HREE could still have a competitive advantage. Hence, the LREE vs. HREE endowment and types of REE bearing minerals will be investigated below.

3.3. *Challenges and opportunities associated with ore mineralogy*

As outlined above (Section 1.3), there are numerous geologically defined REE deposit types with particular associations of REE-bearing minerals. For some of these minerals, which belong to the carbonate and phosphates mineral groups, there are beneficiation technologies in commercial operation. In particular, bastnäsite (carbonate) processing facilities are strongly concentrated in China whereas the monazite (phosphate) produced from the Mount Weld mine in Australia is processed also by facilities located in Malaysia (Lynas Corp). Currently, methods for the beneficiation of REE bearing silicate group minerals are under development and testing, such as in the EURare project (EURare, 2012, 2015a, 2015b). This R & D work is crucial for the conversion of a large part of the newly defined global resources which are associated with silicate ore minerals (Fig. 4).

Information regarding the geological setting of the REE projects and the contained REE bearing minerals has been summarized in Table A2 based on the descriptions by the individual companies. Even though the level of knowledge and disclosure varies it is possible to determine the main REE mineral type for most of the projects within the scope of this general classification. This exercise shows that there are 12 projects with carbonates as the main REE bearing mineral, whereas 16 projects are dominated by phosphates and 15 projects contain mainly REE silicates (6 projects could not be classified). Considering the distribution of the contained REO in these different types of resources it is apparent that about 50% (50.7 Mt) are related to REE bearing silicate minerals whereas deposits with carbonate REE bearing minerals represent about one third (28.7 Mt). A further 16.5 Mt are associated with resources containing dominantly phosphate REE bearing minerals (2.1 Mt in unclassified resources; Fig. 4).

There are substantial regional differences in the distribution of REE resource types (Fig. 4). The REE resources of Greenland are almost exclusively in deposits with silicates as the principal REE bearing mineral whereas in Canada deposits with REE carbonates are dominant (22 Mt of the 38 Mt total for Canada). However, in Canada there

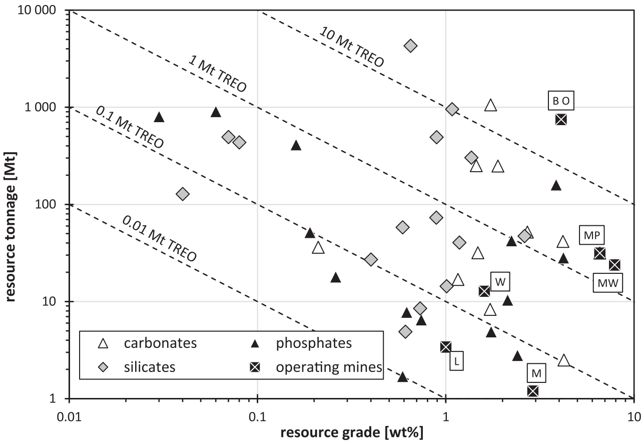


Fig. 5. Tonnage and grade characteristics of REE projects defined outside of China during the recent exploration boom show some systematic trends according to the REE bearing minerals in the resources. Projects dominated by REE carbonates are at the high end of the grade spectrum ranging from 1 to 6.6 wt%. In contrast, REE silicate deposits typically have lower grades, typically around 1 wt% or less. Abbreviations as in Fig. 3.

are also significant resources associated with silicates (9.3 Mt) and phosphates (4.7 Mt). African REE resources are mainly associated with REE phosphates and REE carbonates, and REE resources in the USA are mainly associated with REE carbonates. The Australian REE resources are dominated by phosphate and silicate REE bearing minerals.

Furthermore, there are significant differences in tonnage and grade that correlate with REE mineralogy (Fig. 5). Resources dominated by REE-bearing carbonates generally have REE grades > 1 wt% and the resource at Mountain Pass (USA, Molycorp) is at the upper end of the spectrum (6.6 wt%). In contrast, typical grades of resources with REE-bearing silicates are around 1 wt% or less. Resource with REE phosphates show resource grades ranging from < 0.1 wt% up to 7.8 wt% (i.e., the resource of the operating Mount Weld mine).

An investigation of the relative distribution of LREO and HREO among the different resources as defined by predominant REE bearing mineral type demonstrate particular characteristics (Fig. 6): The resources characterized by REE bearing carbonates show strong enrichments in LREO with LREO/HREO ratios ranging mainly from 10 to 100. In contrast, resources with higher relative HREO contents (LREO/HREO between 10 and 1) are dominated by REE bearing phosphates and silicates. Most of the deposits with LREO/HREO ratios < 10 (i.e, comparatively enriched in HREO) are relatively small with less than 1 Mt of contained TREO (14 projects of a total of 19). However, there are 5 deposits in this “elevate HREO” group that range in TREO tonnage from 4.1 Mt to 28 Mt (Table A2). Of these, four are dominated by silicate REE bearing minerals (Kringlerne and Kvanefjeld in Greenland; Nechalacho and Strange Lake in Canada) and one by REE phosphates (Mrima Hill, Tanzania).

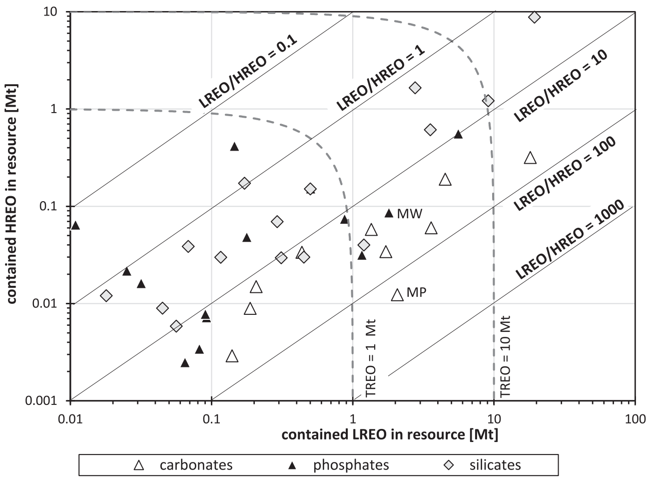


Fig. 6. There are systematic differences in terms of LREO/HREO ratios depending on the dominant REE-bearing mineral of the resource. Resources that are dominated by carbonate REE minerals are strongly enriched in LREO relative to HREO. In contrast, resource with REE silicates or REE phosphates have more balanced REE proportions and some are even HREE enriched (LREO/HREO mostly ranging from 10 to 0.1). Some of the projects with LREO/HREO < 10 are also of substantial tonnage and associated with silicate REE bearing minerals (Kringlerne and Kvanefjeld, Greenland; Strange Lake and Nechalacho, Canada; Tables A1 and A2).

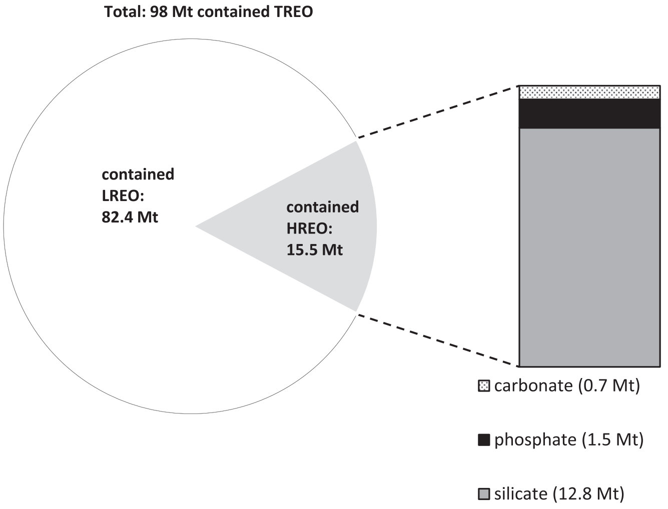


Fig. 7. The total of 98 Mt TREO defined during the REE exploration boom consist mainly of LREO and a smaller fraction of HREO. The contained HREO (15.5 Mt) are strongly concentrated in resources that have silicates as the main REE ore mineral (Table A2).

The particular importance of REE-bearing silicates becomes even more apparent when the overall proportions of contained LREO and HREO in the resources defined during the exploration boom are considered (Fig. 7). The total sum of 98 Mt contained REO consists of 82.4 Mt LREO and 15.5 Mt HREO. More than 80% of the HREO (12.8 Mt) are contained in resources that have silicates as the main REE bearing mineral. Clearly, development of industrial-scale beneficiation technology for REE-bearing silicates would have a significant impact on the supply of HREO.

In summary, it is important to realize that many of the REE resources defined outside of China consist of REE-bearing silicates and phosphates and have a higher proportion of HREO than the traditional, carbonate (i.e., bastnäsite) -dominated REE resources that are the current focus of exploitation (e.g., Bayan Obo deposit). This means that, despite the overall lower grade of many resources with REE-bearing silicates, it could be viable to develop such deposits due to the higher value REE spectrum (i.e., higher HREO content of these resources). Therefore, we investigate the resource value characteristics in some more detail in the following section.

4. Economic considerations

A nominal value of a given mineral resource in the ground can be calculated by multiplying the amount of metal/element contained by the commodity price (Section 2). However, this value has limited use in mine development feasibility studies since numerous additional factors including recovery rates, operation costs, geometallurgy of the ore, mining technology, investment needs, infrastructure and distance from market influence whether an operation can be profitably implemented.

Despite these limitations, this metric is a useful first-order indicator when comparing mineral resources of a given mineral raw material type and in time series studies. In the following, we consider the "in ground value" of the REE resources defined during the exploration boom using the annual average prices for 2011 (peak price environment) and 2015 (prices close to or below long term averages).

4.1. *Effects of changing REE prices and the value of REE resources*

The total "in ground value" of the resource defined during the REE exploration boom, in 2011 prices, was in the order of USD 17 trillion (Table A2). With annual prices for 2015 this value dropped to USD 1.8 trillion. In other words, in 2015, the same resources were valued at only a tenth of their 2011 value which highlights the difficulty in making long term predictions regarding mineral raw material prices especially in minor metal markets.

In the case of REE mining, there is the additional complicating factor that price developments are not necessarily linked exclusively to changes in supply and demand. It is quite feasible to imagine another period of real or perceived supply shortage since the overall situation of the REE mining market has not changed significantly (i.e., the market continues to be dominated by China). However, there are also indications that the potential for China to influence REE prices is limited (Zhü et al., 2016). Nevertheless, it can be argued that the value of the REE resources outside of China is strongly tied to global economic and political developments since the main criticality parameters remain unchanged (i.e., high strategic industrial importance combined with limited supply options). As such, the 2011 and 2015 data may represent order of magnitude indicators for the upper and lower limits regarding valuation of these REE resources.

For exploration companies active outside of China, this general situation has a profound impact on the potential to secure investments for capital expenditure required to work towards mine development. Ernst and Young (2011) argued that only a few REE exploration companies will be able to pursue public equity raising and/or equity stake disposal for offers of future offtake agreements. Hence, a large portion of the REE companies will need to pursue a partial or full exit strategy by selling the project (Ernst and Young, 2011). This is a reflection of the lacking participation of larger mining companies with income from producing mines in the REE exploration, and of the more prevalent participation of junior exploration companies which lack assets that could be used as collateral in funding mine developments.

In order to further address the question of which REE resources may have the best chances of eventual exploitation it is worthwhile to return to the observed differences in REE spectra related to the type of the predominant REE-bearing mineral and the variation in grade of the resources. Here, we investigate relationships with two parameters: basket price (USD/kilogram of contained TREO) and value of an average tonne of the resource (Fig. 8a–c). Note that in this scenario the basket price should be regarded as a maximum estimate since it includes the LREE cerium and lanthanum even though these are currently difficult to sell due to oversupply that is reflected in record-low prices.

For 2011, the basket price data show a spread from USD 120 to USD 320 with the resources dominated by REE bearing carbonates at the lower end of the spectrum (Fig. 8A). Most of the silicate and phosphate-dominated deposits are in the range of USD 150 to USD 250, however, the upper end is occupied by some phosphate-dominated deposits (Brockmans, Australia; Browns Range, Australia; Kutessay II, Kazakhstan; Lofdal, Namibia). Interestingly, the resources at Mountain Pass and Mount Weld are in the lower portion of the basket price spectrum.

The general characteristics of this distribution remain largely unchanged in 2015, however, the spread is now from USD 10 to USD 40 (Fig. 8B). Also, the value loss measured by basket price has been higher for strongly LREE enriched carbonate deposits (e.g., Mountain Pass dropped by 92% from USD 132 to USD 11; Brockmans dropped by 87% from USD 309 to USD 39).

From this observation, it would appear that some of the silicate and phosphate-dominated resources are of higher relative value compared to their peers and could have a stronger chance at remaining profitable mining operations during price downturns. However, a somewhat different picture emerges when the value per tonne of the resource is considered (Fig. 8C). By this metric, both the characteristics of the REE spectrum and the grade of the deposit are reflected. As for the basket price, there is a severe reduction in USD/t values when comparing data from 2011 and 2015 (Table A2), however, the relative valuation of the resources is significantly different. It emerges that Mountain Pass and Mount Weld are in fact high value deposits in this metric compared to their peers with per tonne values of USD 740 (Mountain Pass) and USD 1370 (Mount Weld) in 2015. The silicate-dominated deposits are mainly in the range of USD 100–300 per tonne, reflecting the comparatively low average grades of such deposits. For deposits with phosphate-bearing REE minerals, a large variability is apparent including deposits with < USD 50 but also deposits with values around USD 600/t (Araxá, Brazil and Mriam Hill, Kenya). Another deposit with a high value per tonne is Ngualla (Tanzania) which is dominated by carbonate REE bearing minerals. However, it is remarkable how clearly the Mount Weld deposit stands out compared to its peers in this parameter. The relatively high average grade of the deposit (7.9 wt%, Fig. 5, Table A2) combined with a more favorable REE spectrum compared to Mountain Pass (Fig. 6, Table A1) are important factors that contribute to the resilience of this mining operation even under the current low price conditions.

Considering basket price and value per tonne characteristics provides some first order insights regarding the potential viability of eventual exploitation of the REE resource delineated outside of China. Importantly, some of the projects considered in this study have reached the feasibility stage and published expected operation costs range from USD 6–50 per kilogram REO (compiled by Bogner (2015)). Comparing the estimated operation costs and basket price it is interesting to note that it is not necessarily the "higher value" (i.e., higher basket price) projects that are above the "break even" line (Fig. 8D). Rather, 6 of the 7 projects with basket price values below USD 20 have projected operational costs that indicate a positive revenue. In contrast, for the 7 projects with basket price values in the USD 20–40 range there are only 2 projects for which a positive revenue could be expected. These systematics are likely a reflection of differences in grade, REE spectrum, ore mineralogy and project-specific factors (e.g., accessibility, infrastructure, mining and beneficiation methods).

It is also noteworthy that many of the resources with USD/kg values > 20 are associated with REE bearing silicates, especially when considering the larger deposits (> 1 Mt TREO contained; Fig. 8A and B). Here, substantial investments in R & D are still required in order to develop, up-scale and optimize mineral processing and beneficiation technologies. Hence, with significant technology development, operation cost for these types of deposits might be reduced. Yet, investment for R & D work and high-risk capital expenditure in the REE sector appears challenging to secure during the current low price environment.

4.2. *How much did the REE exploration boom cost?*

The search for mineral deposits and the definition of resources is generally considered an investment from which profits can be reaped at later points in development. During periods of high commodity prices, junior exploration companies have the possibility to access market financing for their activities, e.g., via public stock market equity

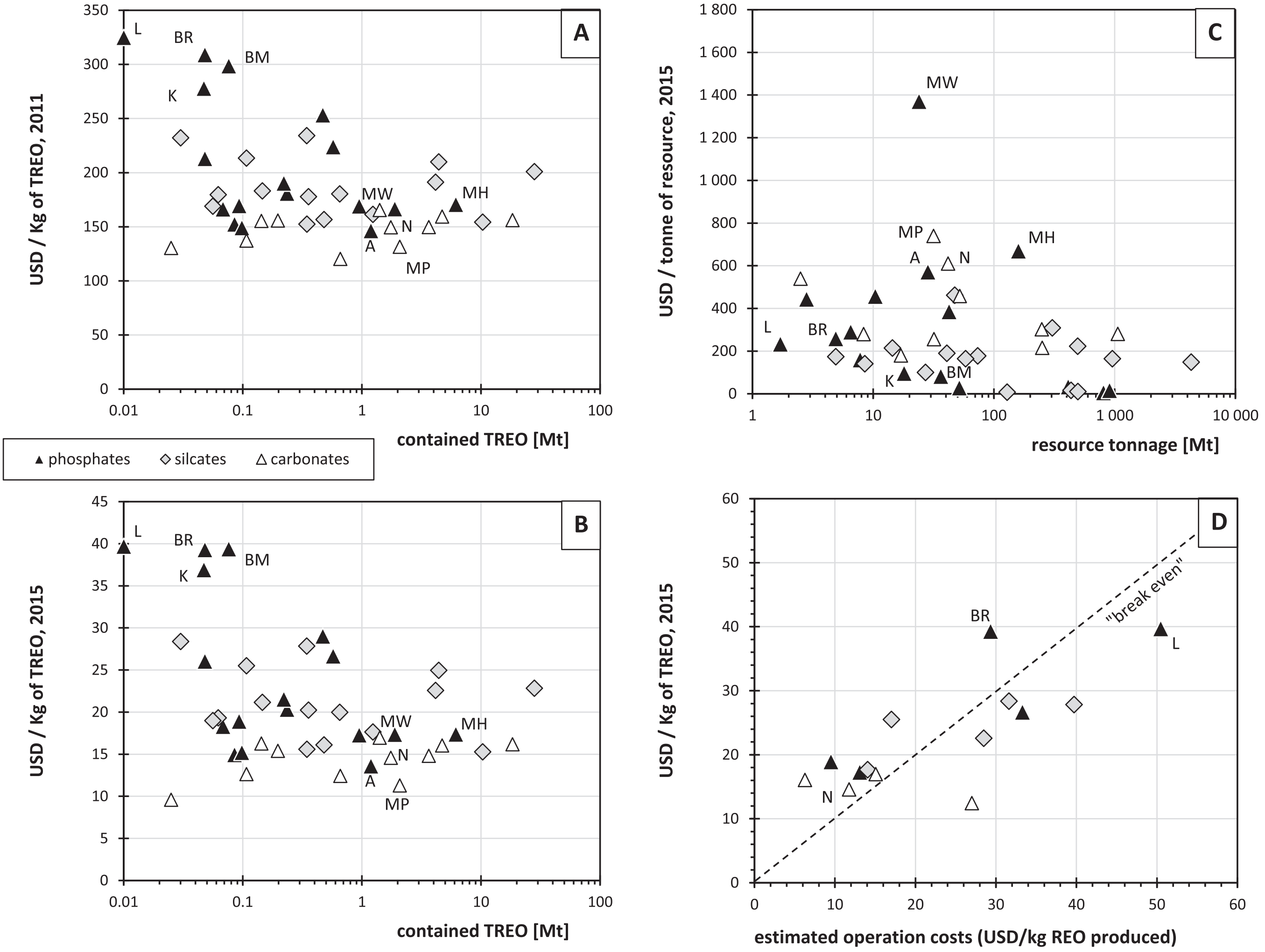


Fig. 8. Comparison of normalized "in ground value" of REE resources defined during the REE exploration boom for 2011 and 2015. It is important to note that resources with a high basket price do not necessarily have a high value per tonne which is linked to the tonnage and grade systematics. A) and B) value of one kilogram of the TREO contained ("basket price") vs. amount of TREO contained. C) value of one average tonne of the resource vs. resource size and D) comparison of expected operating costs (per kg of TREO produced; data from Bogner (2015)) and current basket price. Operating cost estimates are available for the following projects (in order of increasing costs): Steenskampskraal: 9.50 USD; Nguall: 12 USD; Zandkopsdrift: 13 USD; Nolans: 14 USD; Bear Lodge: 15 USD; Kipawa: 17 USD; Songwe Hill: 27 USD; Nechalacho: 28 USD; Browns Range: 29 USD; Bokan: 32 USD; Round Top: 33 USD; Norra Kärr: 40 USD; Lofdal: 50 USD). Abbreviations: BM: Brockmans (Australia), BR: Browns Range (Australia), K: Kutessay II (Kazakhstan), L: Lofdal (Namibia), MP: Mountain Pass (USA), MW: Mount Weld (Australia). Note that the Steenskampskraal project (South Africa; 0.7 Mt at 14 wt% TREO) and the Wigu Hill Twiga deposit (Tanzania; 0.5 Mt, 5.27 wt% TREO grade) are plotting outside of Fig. 8C.

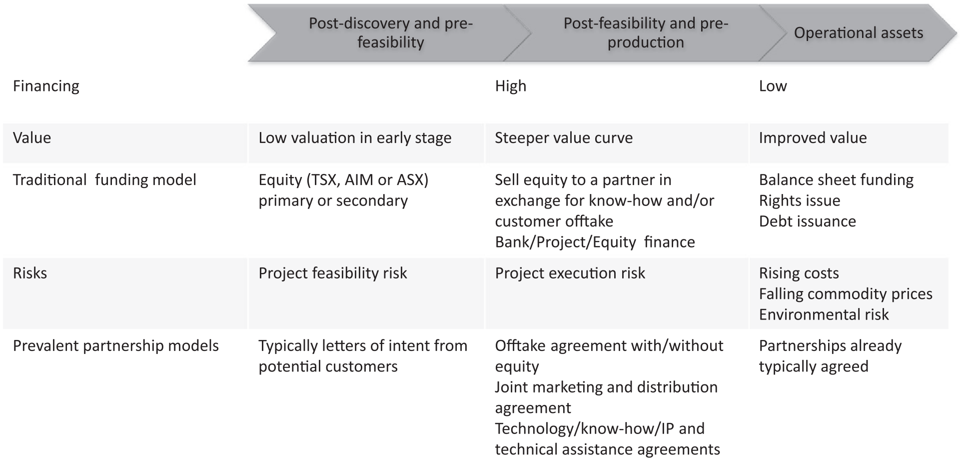
placements. During the last global upswing in commodity prices (c. 2006–2012), global exploration budgets for nonferrous metals soared, reaching a peak of about USD 21 billion in 2012 (SNL Metals and Mining, 2015). Hence, the REE exploration boom occurred at a time when investment in mineral exploration was at an all-time high. More than 200 REE-focused junior exploration companies were listed on the Toronto stock exchange during 2011 (Hatch, 2012). Yet, only a fraction of these companies has been successful in defining REE resources during their exploration activities.

The compiled REE resources (TMR, 2015) are part of the portfolio of publicly listed companies, and some privately held entities. Their activities are funded by investors seeking a profit from their placements, and, in general, the deposit valuation will augment significantly between the discovery stage and the completion of the bankable feasibility study (Ernst and Young, 2011).

The high risk associated with mineral exploration is correlated with the outlook for high profits. Short-term investors, so-called speculators, are particularly drawn to this type of investment, yet their prime interest lies in achieving a high profit return on investment over a short period of time, rather than in the development of a mine. These types of investors benefit therefore from selling their shares at a profit between the first and the second phase illustrated in Fig. 9. Only a fraction of exploration projects eventually develop into mining operations (phase three in Fig. 9), and long-term investors would receive dividends when the mining operation generates a profit.

Other forms of capitalizing on investments in the junior resource sector include exit strategies such as mergers and acquisitions by larger mining companies interested in gaining access to particular projects. Furthermore, a high degree of volatility is characteristic for junior stocks in the mining and exploration sector, which is, among other factors, linked to investor decisions in which they weigh financial gains against perceived risk. Hence, there are entry and exit opportunities for speculators seeking short term profits.

In an attempt to quantify the value of REE companies, which can be regarded as a proxy for the amount of funds available for exploration activities, we investigate the developments of their stock prices and market capitalizations from early 2011 to early 2015. The rights to the REE projects listed in Table A2 are held by 44 individual companies of which 37 are publicly listed. Of these, 10 are listed on the Australian stock exchange, 22 on the Toronto stock exchange, 3 are listed in the



	Post-discovery and pre-feasibility	Post-feasibility and pre-production	Operational assets
Financing		High	Low
Value	Low valuation in early stage	Steeper value curve	Improved value
Traditional funding model	Equity (TSX, AIM or ASX) primary or secondary	Sell equity to a partner in exchange for know-how and/or customer offtake Bank/Project/Equity finance	Balance sheet funding Rights issue Debt issuance
Risks	Project feasibility risk	Project execution risk	Rising costs Falling commodity prices Environmental risk
Prevalent partnership models	Typically letters of intent from potential customers	Offtake agreement with/without equity Joint marketing and distribution agreement Technology/know-how/IP and technical assistance agreements	Partnerships already typically agreed

Fig. 9. Explorer perspective on risks and challenges as related to financing. Three distinct phases (post-discovery and pre-feasibility; post-feasibility and pre-production; operational assets) can be identified from the perspective of an exploration company and its activities along resource definition, up to potential mine development. The attributes financing, value, traditional funding model, risks, and prevalent partnership model are evaluated for each of the three phases. Source: modified from Ernst and Young (2011).

USA and 2 are listed in Europe (Table A3). For these companies, the combined market capitalization was in the order of USD 19 billion during spring 2011 (when share prices reached their peak). In contrast, this value was only about 1 billion USD in 2015, representing a 95% decrease.

It appears that most of the investments made available by private and institutional investors to discover and define REE resources outside of China, are currently losses. Furthermore, currently it seems unlikely that the required funds for capital investments could be secured to finance up-front development costs. Our analysis further suggests that many projects will face difficulties in reducing operation costs to the level where positive revenue can be expected (Fig. 8D).

Hence, it seems doubtful that the defined resources will be transformed into producing mines with prospects for dividend payments to long-term investors. It can be inferred that the costs for the REE exploration boom have been covered by those stock market investors which remained with their shareholdings between 2011 and 2015, and, on the balance, incurred substantial losses. The combined total of these losses is challenging to trace accurately since it depends on the background of each individual trade. However, assuming that about 10% of the difference in market capitalization values between 2011 and 2015 are negative revenue, the cost for the REE exploration boom may well be in the order of USD 2 billion. If this analysis was expanded to REE junior exploration companies that have not succeeded in publishing a resource estimate (i.e., the large majority of the total of about 200 companies active in 2012), this value would be significantly higher.

5. Discussion: making sense of the exploration boom

In this paper we argue that the REE exploration boom displayed two distinct characteristics: (1) the definition of substantial silicate REE-bearing mineral ore resources with comparatively higher HREE content, and (2) a correlation of market capitalization of junior exploration companies and in-ground value of the defined resources with the general changes of REE prices (i.e., high during peak price conditions in 2011 and low at currently subdued price levels in 2015). In the following, we discuss how these characteristics can be interpreted.

Demand for HREE on the increase amid industrial consolidation. Arguably, industrial REE demand is shifting towards HREE and driven by the expansive interest in renewable and more efficient energy technologies, which rely, among other, on the magnetic and fluorescent properties of HREE. In this light, and given the high LREE/HREE ratio of traditional REE ore minerals, the definition of new REE deposits with REE-silicate minerals that are comparatively more enriched in HREE is advantageous to industrial development dependent on HREE. This includes manufacturing REE-based magnets for generators in particular direct drive wind turbines, and for REE-based permanent magnet motors used in a wide variety of applications, from hard disc drives to automobiles, industrial motors for conveyor belts, and many more.

With Chinese ambitions to upgrade national industries towards higher value-added high-tech manufacturing, the interest in HREE accessibility is evident. This is particularly accurate amidst anticipations of industrial consolidation that could put a halt on illegal REE mining activities, which would arguably affect the HREE supply from Southern Chinese provinces where relatively HREE rich “ionic clay deposits” are located. The detrimental effect of illegal REE mining, in particular with regard to the contamination of drinking water sources, has been recently highlighted (Liu, 2016). The enforcement of environmental regulations led to the closure of mining operations and the seizure of unregulated REE products (Mining Journal, 2016).

Furthermore, the restricting of mining quota allocations has left some firms with significantly reduced rights and it appears that these are now attempting to gain access to REE-minerals outside China to keep their facilities in operation. This is in line with previous analyses including Chen (2011, p. 5): ‘It can be supposed that after consolidation and with effective total production control of 85 thousand tons in 2013, China will reduce its supply proportion to 64%, and leave the rest 36% to those producers out of China.

Selective interest in REE deposits and REE companies by Chinese stakeholders. In this light it is useful to remember expressed prior interest by Chinese stakeholders in the REE-deposit of Mount Weld (Kirchner, 2014), yet not of Mountain Pass, but rather in Magnequench, the REE-magnet manufacturer (for a detailed discussion of the latter see Machacek and Fold (2014)). This variegated interest might be explained by Fig. 8 in which we demonstrate the higher value of the phosphate REE-bearing minerals at Mount Weld, as compared to the lower value of the carbonate REE-bearing minerals at Mountain Pass.

Given the significant reductions in market values of the REE-bearing mineral deposits as shown in Table A2, and in Fig. 8b due to REE price decreases since the peak, it could be hypothesized that some deposits are of more interest for acquisition than others, and in this context, we could specifically examine a selected silicate-mineral ore project (Kvanefjeld by Greenland Minerals and Energy Ltd. (GMEL)) for which trial separation processes were financed by the EU-project

EURare. These were executed recently by Outotec and GTK in Finland, with follow-up beneficiation at MEAB and RWTH Aachen in Germany (EURare, 2015a, 2015b).

The case of Kvanefjeld (Greenland). Interest has been expressed in the Kvanefjeld project in the form of a second memorandum of understanding signed between China Non-Ferrous Metal Industry's Foreign Engineering and Construction Co. Ltd. (NFC), and GMEL, an Australian registered junior exploration firm with exploration rights in the Kvanefjeld deposit of South Greenland (GME Ltd., 2015). This engagement might be understood in the context of higher strategic interest in relatively HREE enriched mineral deposits for future demand in China.

The MoU refers, among other, to the 'extensive exchange of technical data relating to the Kvanefjeld Project' (GME Ltd., 2015) and assigns GMEL the responsibility of finalizing the exploitation license application, commencing the permitting process, and completing pilot plant operations to confirm the proposed process flow sheet. NFC's participation in the REE industry occurs via its subsidiary Guangdong Zhujiang Rare Earths Company, which has initiated the construction of a 7 000 tpa capacity rare earth separation facility in China to cater to e.g. a REE bearing silicate mineral concentrate which could be produced from Kvanefjeld.

In the context of an analysis by Ernst and Young (2011, p. 20) that only a small number of REE exploration firms will successfully raise public equity and/or dispose equity stakes for future offtake agreements, this second MoU between GMEL and NFC could also be viewed from the perspective of a full or partial exit strategy for GMEL. Questions remain then for the extent to which the interest of NFC in pursuing its MoU remains, should consolidation strategies not be implemented as planned in China, for reasons of conflicts of interests arising from structural challenges in the Chinese industrial organization (latter is discussed by Wübbecke (2013), Mancheri et al. (2013), and Packey and Kingsnorth (2016)).

The market capitalization of ideas and balancing knowledge. A second characteristic of the REE exploration boom illustrated in this paper, the significant augment in junior exploration firms' market capitalization, could be viewed through achieved gains: Specifically, the financing of ideas of developing alternative mining projects to the quasi-monopoly/de-facto monopoly of China were turned into augmented knowledge and achieved definitions of new REE-bearing mineral deposits with comparatively higher HREE content. Arguably, the idea of creating stability amidst uncertainties as to Chinese industrial policy, channeled monetary flows into materialized knowledge in form of augmented resource definitions.

While the in-ground value of these resources has significantly decreased due to low REE prices, the existence of knowledge on these new deposits could also be viewed as an achievement in 'balancing power' by matching the known, mapped REE-resources of China, with new and updated knowledge on REE deposits outside of China. For instance, Hayes-Labruto et al. (2013, p. 57) in their analysis from a Chinese stakeholder perspective, point to a 'varying distribution of responsibility' from the view of reserves held by different countries.

Standardization of the REE industry? Recent discussions among researchers and industry participants have also centered on whether standards are to be designed for the REE-industry, initially REE product standards, followed, potentially, by REE-processing standards. While standards are a means of regulation, including for market access, with the potential to benefit industrial frontrunners, in the case of the REE industry, they are argued to be an opportunity for achieving some control over the industry. Yet, to which extent a product as opposed to a process standard can reach this objective requires a thorough analysis.

It is important to realize that most of the facilities for cracking, processing and refining the primary REE-mineral ore into saleable products, often high purity individual REE-oxides, are located in China. This is, among political interests, a result of a pursued market concentration process of the REE industry, supported also by the particularities of REE-occurrences in China, which initiated during the 1990s. Hence, the option to mine REE ore minerals outside China represents only one step into the direction of diversifying the REE market.

Small steps are underway to strengthen processing facilities for REE elsewhere (e.g. by Lynas in Australia and Malaysia), which constitute a small fraction of the global market. Low REE prices exert substantial pressure on these companies. Will any of these companies holding the rights to REE resource outside of China be able to withstand a significant phase of lower prices, in the arguably quasi-monopolistic situation? In the following, we discuss which role the defined, relatively higher in HREE-enriched resources could assume in this process.

Strategies to maintain the REE industry dominance by China. A high degree of integration and concentration of the REE market provides power to maintain the Chinese "quasi-monopoly". However, supply from Chinese REE resources could become subjected to pressure (1) under stringent regulation to reduce environmental damages e.g. from HREE leaching of ion-adsorption clays, and (2) decreased iron ore prices which affect the mining operations at Bayan Obo which compete with high volume/low-cost supply from Western Australia (further unfolded by Packey and Kingsnorth (2016)). These issues could be counteracted by increased exploration efforts in other REE fertile geological areas within China (e.g., Maoniuping, Weishan).

Alternatively, it may be attractive to source REE bearing mineral ore from external resources for the Chinese REE processing and separation industry. As has been demonstrated, REE resources have been successfully defined including traditional REE bearing minerals (bastnäsite, xenotime, monazite) and non-traditional silicate and oxides REE bearing minerals. Given the well-established expertise in processing REE minerals, it seems likely that new methods for treating non-traditional types of minerals from the recently defined resources could be commercialized in China, as described on the case of GMEL and NFC.

Companies holding the rights to the defined REE resources outside of China currently experience low market capitalizations and struggle with raising funds for the high CAPEX required to finalize their feasibility studies, start the actual mining operation and construct beneficiation and separation infrastructure. Their share prices are typically only a fraction of the peak notations, e.g. in the case of Molycorp from about 80 USD in 2011 to less than 1 USD in 2015. This means that investors looking at feeding REE mineral supply to existing Chinese processing facilities are presented with a multitude of low cost buying opportunities.

Potential gains from mining and processing unconventional REE bearing minerals enriched in HREE. For REE resources dominated by REE silicate ore minerals there is a need for research and development to establish processing and beneficiation methods on a commercial scale. Mainly, substantial upscaling is required to move "bench-top" solutions to viable large scale operations. The financial risk involved in investing in such research, in the context of a rather uncertain share of illegal REE production in China feeding global demand, leaves little incentive to investors to finance the commercialization and implementation of beneficiation techniques of unconventional higher enriched HREE minerals. This situation could be addressed by political support for initiatives that facilitate R & D and commercialization, yet it is contested for various reasons (ERECON, 2014).

A counter-argument hardly explicitly addressed so far, however, evolves around the possibility of regaining a foothold in REE processing, including for existing separation capacity outside China. From a historical perspective, REE separation technologies and environmental regulations, specifically restrictions on raw material imports with radioactive content, determined the geographical shift in REE industry governance, from the U.S. and Europe/Australia, respectively, to China in the 1990s.

With investments in research and development toward the commercializing of beneficiation technologies of unconventional higher enriched HREE mineral ore, could historical players not only build on their remaining presence of knowledge on REE separation technology, but also participate in a technology race which could open pathways for innovative activity. Such activity could yield untapped potential for new discoveries of e.g. unexplored potentials of some HREE, such as Lu, Er, Yb for the development of advanced materials.

Further, along the same argument, to have a supply of HREE originating from some of the silicate mineral ore bearing mines outside of China could provide a degree of 'self-sufficiency' to key industrial activities such as catalyst manufacturing and development in Europe, yet with a supply of relatively more HREE than LREE enriched mineral ore that matches e.g. the needs of European industrial demand more closely.

With the abundance of REE mineral resources in Canada and Greenland it might be envisioned that processed material from these areas could be transported to NE Asia via newly accessible Arctic shipping routes ("NW passage"). In this regard, the recently signed European-Canadian free trade agreement may also present possibilities for the REE industry. In essence, the newly defined REE resources provide opportunities for developing REE supply for the global REE market from sources outside of China.

6. Conclusion

In this paper, we examined the surge in REE exploration activities carried out by junior exploration companies which secured funding from stock markets during REE peak price conditions. This coincided with a phase of generally high levels of global mineral resource exploration. The investments in the REE exploration sector led to the definition of about 98 Mt of REO in resources outside of China within 5 years (2011–2015), demonstrating the capacity of the junior exploration sector to react quickly to price dynamics in the mineral raw material market.

Our detailed investigation of geological, economic and strategic issues pinpoint the following issues:

1) REE deposits are fairly common outside of China. However, in terms of resource tonnages and average grade there are only a few that are comparable to current producing mines.
2) Funding for exploration activities was readily available from the public stock exchange at the time when REE prices were rising, nurturing hopes for high returns on investments.
3) REE resources were defined in many countries, however, the highest concentration of newly defined TREO resources are in Canada (38 Mt), Greenland (36 Mt) and Africa (Kenya, Tanzania, Malawi, South Africa; 10 Mt). Combined, this represents a fivefold increase compared to estimates from 2010 for these jurisdictions.
4) Since their peak in 2011, REE prices declined substantially and global production appears to have stabilize at about 110,000 t/a. Concurrently, there is a substantial decrease in public interest in stocks of REE companies. The REE producers that managed to kick-start REE mining and processing outside of China are affected by declining share prices (e.g. Molycorp, USA; Lynas, Australia), as well as companies pursuing project development and feasibility studies.
5) In the current situation, an opportunity presents itself to acquire REE resources to secure long term supply of REE bearing minerals: Investors with processing facilities can choose from a broad range of defined REE deposits at bottom-of-the-market prices, illustrated on the case of Australian registered GMEL and Chinese NFC. This opportunity arises in the context of REE mining production in China that is under pressure to meet stringent environmental legislation, limited mining quota allocation to some REE processing operations due to consolidation plans, and challenges for REE mining at the important Bayan Obo mine. At Bayan Obo, REE are a by-product of iron ore mining, exploiting a comparatively low-grade Fe resource, which faces competition from high-grade iron ore production in Australia.

Overall, the net effect of the situation suggests that the country with the most highly integrated REE market from mining to processing, and use in the manufacturing of electronics and high-tech industry may realize most benefit from the resource definitions achieved by the global REE exploration boom. Hence, the investments in junior companies to fund REE exploration activities have arguably only one country that is well enough positioned to take advantage: China.

Acknowledgements

The development of our ideas related to the global REE exploration efforts has benefited greatly from discussions with many colleagues at the Geological Survey of Denmark and Greenland (GEUS), at Curtin University, and with representatives of REE exploration companies. In particular, we would like to thank Per Kalvig (MiMa-GEUS), Anouk Borst (University of St Andrews), Dudley J. Kingsnorth (Curtin University), Greg Barnes (Tanbreez), and Damien Krebs (GME Ltd.) for sharing their insights, and supplying data on REE market developments. Normann Schadock is thanked for his assistance with collecting geological data for the REE projects during his internship at GEUS. We also acknowledge constructive criticism and suggestions for improvements provided during the review process.

Appendix A

See Tables A1–A3.

Table A1
Data for REE resources outside China (compiled from TMR (2015)).

Country	Deposit	Status (2015)	License holder	Resource			Grades of individual REO (wt%)														
				(Mt)	TREO (wt%)	TREO (Mt)	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3
AUS	Browns Range	expl.	Northern Minerals Limited	6.5	0.74	0.05	0.018	0.044	0.006	0.028	0.016	0.003	0.042	0.009	0.062	0.014	0.039	0.006	0.032	0.004	0.416
AUS	Charley Creek	expl.	Crossland Strategic Metals Ltd.; Pancontinental Uranium Corporation	805	0.03	0.24	0.005	0.011	0.001	0.004	0.001	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.004
AUS	Cummins Range	expl.	Navigator Resources Limited	4.9	1.74	0.09	0.468	0.814	0.084	0.273	0.033	0.006	0.020	0.000	0.009	0.000	0.001	0.000	0.000	0.000	0.034
AUS	Mount Weld*	REE mine	Lynas Corporation Ltd.	23.9	7.89	1.89	1.901	3.600	0.400	1.425	0.199	0.046	0.102	0.011	0.038	0.005	0.011	0.001	0.005	0.000	0.140
AUS	Dubbo	expl.	Alkane Resources Ltd.	73.2	0.89	0.65	0.174	0.328	0.036	0.126	0.019	0.001	0.019	0.003	0.018	0.003	0.010	0.001	0.009	0.001	0.141
AUS	Nolans Bore	expl.	Arafura Resources Ltd.	47.2	2.62	1.24	0.501	1.277	0.155	0.539	0.060	0.010	0.026	0.002	0.008	0.001	0.002	0.000	0.001	0.000	0.035
AUS	Hastings	expl.	Hastings Rare Metals Limited	36.2	0.21	0.08	0.003	0.013	0.002	0.007	0.005	0.000	0.007	0.002	0.019	0.004	0.017	0.002	0.014	0.002	0.112
AUS	Milo	expl.	GBM Resources Ltd.	187	0.06	0.12	0.015	0.026	0.002	0.008	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.005
CAN	Elliott Lake	expl.	Appia Energy Corp.	51.6	0.19	0.10	0.048	0.088	0.009	0.028	0.005	0.000	0.003	0.000	0.002	0.000	0.001	0.000	0.001	0.000	0.007
CAN	Hoidas Lake	expl.	Great Western Minerals Group Ltd.; Star Minerals Group Ltd.	2.8	2.40	0.07	0.491	1.120	0.143	0.494	0.065	0.013	0.030	0.003	0.008	0.000	0.006	0.000	0.001	0.000	0.028
CAN	Foxtrot	expl.	Search Minerals Inc.	14.4	1.01	0.15	0.183	0.390	0.044	0.160	0.029	0.001	0.023	0.004	0.021	0.004	0.012	0.002	0.010	0.002	0.129
CAN	Kipawa	expl.	Matamec Explorations Inc.	27.1	0.40	0.11	0.057	0.116	0.014	0.053	0.012	0.001	0.012	0.002	0.014	0.003	0.010	0.001	0.010	0.001	0.089
CAN	Clay-Howells	expl.	Canada Rare Earth Corp.	8.5	0.73	0.06	0.183	0.318	0.032	0.110	0.017	0.004	0.011	0.004	0.007	0.001	0.003	0.000	0.003	0.000	0.036
CAN	Two Tom	expl.	Canada Rare Earth Corp.	40.6	1.18	0.48	0.288	0.544	0.056	0.188	0.032	0.003	0.019	0.002	0.008	0.001	0.002	0.000	0.001	0.000	0.038
CAN	Nechalacho (Thor Lake)*	expl.	Avalon Rare Metals Inc.	303	1.37	4.14	0.238	0.547	0.067	0.263	0.051	0.006	0.041	0.005	0.024	0.004	0.010	0.001	0.008	0.001	0.101
CAN	Strange Lake*	expl.	Quest Rare Minerals Ltd.	492	0.89	4.40	0.121	0.274	0.030	0.111	0.024	0.001	0.024	0.005	0.031	0.007	0.022	0.003	0.022	0.003	0.217
CAN	Ashram*	expl.	Commerce Resources Corp.	249	1.89	4.71	0.490	0.877	0.091	0.313	0.039	0.009	0.021	0.002	0.008	0.001	0.002	0.000	0.001	0.000	0.031
CAN	Lavergne-Springer	expl.	Canada Rare Earth Corp.	16.9	1.16	0.20	0.311	0.536	0.055	0.185	0.022	0.005	0.012	0.001	0.005	0.001	0.002	0.000	0.001	0.000	0.026
CAN	Niobec	Nb mine	Niobec (Magris Resources)	1058	1.73	18.36	0.425	0.830	0.092	0.321	0.036	0.007	0.017	0.001	0.005	0.000	0.000	0.000	0.000	0.000	0.000
CAN	Montviel	expl.	Geomega Resources Inc.	251	1.45	3.65	0.372	0.716	0.075	0.242	0.025	0.005	0.008	0.001	0.002	0.000	0.001	0.000	0.000	0.000	0.007

(continued on next page)

Table A1 *(continued)*

Country	Deposit	Status (2015)	License holder	Resource			Grades of individual REO (wt%)														
				(Mt)	TREO (wt%)	TREO (Mt)	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3
CAN	Buckton*	expl.	DNI Metals Inc.	3930	0.03	1.18	0.005	0.008	0.001	0.004	0.001	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.004
CAN	Grande-Vallée	expl.	Orbite Aluminae Inc.	1210	0.05	0.61	0.009	0.019	0.002	0.009	0.002	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.006
CAN	Eco Ridge	expl.	Pele Mountain Resources Inc.	59.3	0.16	0.09	0.037	0.071	0.007	0.023	0.004	0.000	0.003	0.000	0.002	0.000	0.001	0.000	0.001	0.000	0.008
USA	Round Top	expl.	Texas Rare Earth Resources Corp.	906	0.06	0.57	0.002	0.009	0.001	0.003	0.001	0.000	0.001	0.000	0.004	0.001	0.004	0.001	0.006	0.001	0.028
USA	Bokan	expl.	Ucore Rare Metals Inc.	4.9	0.61	0.03	0.070	0.170	0.020	0.084	0.022	0.002	0.023	0.004	0.026	0.006	0.014	0.002	0.010	0.001	0.158
USA	La Paz	expl.	AusAmerican Mining Corp. Ltd.	128	0.04	0.06	0.008	0.017	0.002	0.007	0.001	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.005
USA	Mountain Pass	REE mine	Molycorp Inc.	31.6	6.57	2.07	2.180	3.224	0.282	0.788	0.053	0.007	0.013	0.004	0.003	0.001	0.001	0.001	0.001	0.001	0.007
USA	Bear Lodge	expl.	Rare Element Resources Ltd.	52.1	2.71	1.41	0.715	1.184	0.133	0.484	0.078	0.017	0.041	0.003	0.011	0.001	0.002	0.000	0.001	0.000	0.035
KEN	Mrima Hill*	expl.	Pacific Wildcat Resources Corp.	159.4	3.86	6.15	1.955	1.656	0.173	0.580	0.081	0.022	0.058	0.008	0.035	0.006	0.015	0.002	0.010	0.001	0.1924
MDG	Tantalus	expl.	Tantalus Rare Earths AG	435	0.08	0.36	0.017	0.031	0.004	0.013	0.002	0.000	0.002	0.000	0.002	0.000	0.001	0.000	0.001	0.000	0.010
MOZ	Xiluvo	expl.	Promac Lda.	1.1	2.03	0.02	0.440	0.940	0.100	0.350	0.050	0.010	0.030	0.000	0.020	0.000	0.010	0.000	0.000	0.000	0.080
MWI	Kangankunde	expl.	Lynas Corporation Ltd.	2.5	4.24	0.11	1.262	2.109	0.199	0.594	0.045	0.008	0.015	0.003	0.003	0.000	0.001	0.000	0.000	0.000	0.000
MWI	Songwe Hill	expl.	Mkango Resources Ltd.	31.8	1.48	0.66	0.364	0.659	0.071	0.242	0.035	0.008	0.020	0.002	0.012	0.002	0.004	0.001	0.003	0.000	0.054
NAM	Lofdal	expl.	Namibia Rare Earths Inc.	1.7	0.59	0.01	0.021	0.039	0.004	0.016	0.007	0.006	0.026	0.007	0.048	0.011	0.031	0.005	0.029	0.004	0.341
TZA	Ngualla	expl.	Peak Resources Ltd.	41.7	4.19	1.75	1.136	2.021	0.202	0.683	0.070	0.015	0.032	0.003	0.007	0.001	0.003	0.000	0.001	0.000	0.020
TZA	Wigu Hill Twiga	expl.	Montero Mining and Exploration Ltd.	0.5	5.27	0.03	2.020	2.560	0.190	0.450	0.026	0.006	0.008	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0.007
ZAF	Steenkampskraal	expl.	Great Western Minerals Group Ltd.	0.7	14.00	0.09	2.907	6.340	0.717	2.517	0.402	0.009	0.274	0.030	0.140	0.020	0.041	0.004	0.018	0.002	0.579
ZAF	Zandkopsdrift	expl.	Frontier Rare Earths Ltd.; Korea Resources Corp.	42.5	2.23	0.95	0.566	0.983	0.103	0.354	0.051	0.013	0.032	0.004	0.017	0.003	0.007	0.001	0.005	0.001	0.092
ZAF	Glenover	expl.	Galileo Resources PLC; Fer-Min-Ore (Pty) Ltd.	10.4	2.13	0.22	0.359	0.956	0.122	0.473	0.075	0.019	0.043	0.004	0.016	0.002	0.004	0.000	0.002	0.000	0.054
GRL	Kvanefjeld*	expl.	Greenland Minerals and Energy Ltd.	956	1.08	10.33	0.299	0.458	0.044	0.134	0.017	0.001	0.012	0.002	0.012	0.002	0.006	0.001	0.005	0.002	0.085
GRL	Kringlerne	expl.	Rimbal Pty Ltd	4300	0.65	28.06	0.116	0.217	0.021	0.080	0.015	0.002	0.017	0.003	0.019	0.004	0.016	0.002	0.013	0.002	0.127
GRL	Sarfartoq	expl.	Hudson Resources Inc.	8.3	1.72	0.14	0.371	0.857	0.099	0.323	0.032	0.007	0.017	0.001	0.003	0.000	0.000	0.000	0.000	0.000	0.007
BRA	Araxá	expl.	MBAC Fertilizer	28.3	4.21	1.19	1.180	2.079	0.191	0.583	0.063	0.014	0.029	0.003	0.012	0.002	0.003	0.000	0.002	0.000	0.047

(continued on next page)

Table A1 *(continued)*

Country	Deposit	Status (2015)	License holder	Resource			Grades of individual REO (wt%)														
				(Mt)	TREO (wt%)	TREO (Mt)	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3
			Corp.																		
BRA	Serra Verde	expl.	Mining Ventures Brasil Ltda.	412	0.16	0.47	0.035	0.055	0.007	0.021	0.004	0.000	0.003	0.001	0.003	0.001	0.002	0.000	0.002	0.000	0.025
GER	Storkwitz	expl.	Ceritech	4.5	0.45	0.02	0.124	0.220	0.023	0.064	0.006	0.001	0.005	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.006
KGZ	Kutessay II	expl.	Stans Energy Corp.	18	0.26	0.05	0.044	0.052	0.010	0.022	0.011	0.001	0.009	0.004	0.016	0.001	0.009	0.001	0.009	0.001	0.070
SWE	Olserum	expl.	Tasman Metals Ltd.	7.8	0.62	0.05	0.083	0.189	0.023	0.090	0.021	0.001	0.021	0.004	0.021	0.004	0.012	0.002	0.011	0.002	0.130
SWE	Norra Kärr	expl.	Tasman Metals Ltd.	58.1	0.59	0.34	0.059	0.133	0.017	0.067	0.018	0.002	0.019	0.004	0.025	0.005	0.017	0.003	0.016	0.002	0.204
TUR	Aksu Diamas	expl.	AMR Mineral Metal Inc.	494	0.07	0.35	0.018	0.031	0.003	0.010	0.001	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.004

Data from TMR (2015). Abbreviations: AUS: Australia; BRA: Brazil; CAN: Canada; GER: Germany; GRL: Greenland; KEN: Kenia; KGZ: Kyrgyzstan; MDG: Madagascar; MWI: Malawi; MOZ: Mozambique; SWE: Sweden; TUR: Turkey; TZA: Tanzania; USA: United States of America; ZAF: South Africa.

*: Mount Weld: combined resource for Mount Weld CLD and Mount Weld Duncan; Nechalacho: combined resource for Nechalacho Basal and Nechalacho Upper; Strange Lake: combined resource for Stange Lake Enriched and Strange Lake Granite; Ashram: combined resource for Ashram Main and Ashram MHREO; Buckton: combined resource for Buckton and Buckton South; Mrima Hill: combined resource for Mrima Hill High Grade and Mrima Hill Main; Kvanefjeld: combined resource for Kvanefjeld, Sørensen, and Zone 3.

Table A2
Summary of REE resource characteristics and value data.

Region-Country	Deposit	Resource data					Geology data			Financial data					
		(Mt)	grade TREO (wt%)	TREO (Mt)	TLREO (Mt)	THREO (Mt)	Deposit type description[1)]	REE-minerals[2)]	Main REE mineral types[2)]	IGV (2011) (MUSD)	IGV (2015) (MUSD)	Value pt (2011) (USD)	Value pt (2015) (USD)	BP (2011) (USD/ Kg)	BP (2015) (USD/ Kg)
AUS	Browns Range	6.5	0.74	0.048	0.007	0.041	breccia-hosted hydrothermal system	xenotime	phosphates	14,837	1886	2283	290	309	39
AUS	Charley Creek	805.3	0.03	0.235	0.177	0.048	alluvial	monazite, xenotime	phosphates	42,544	4779	53	6	181	20
AUS	Cummins Range	4.9	1.74	0.085	0.082	0.003	carbonatite	monazite	phosphates	12,972	1269	2647	259	153	15
AUS	Dubbo	73.2	0.89	0.651	0.500	0.151	Alkaline trachyte complex	bastnasite, yttrium silicates	silicates	117,433	13,004	1604	178	180	20
AUS	Nolans Bore	47.2	2.62	1.236	1.195	0.040	Alkaline trachyte complex	apatite, allanite	silicates	199,566	21,810	4228	462	161	18
AUS	Brockmans	36.2	0.21	0.076	0.011	0.065	tuffaceous rhyolitic volcaniclastic unit	parisite, bastnasite, synchysite	carbonates	22,710	2993	627	83	299	39
AUS	Milo	187	0.06	0.115	0.097	0.017	IOCG-breccia type deposit	?	?	17,724	1792	95	10	154	16
AUS	Mount Weld	23.9	7.9	1.889	1.799	0.086	carbonatite complex	monazite, crandallite, rhabdophane, cerianite, churchite	phosphates	314,680	32,775	13,167	1371	167	17
CAN	Elliott Lake	51.6	0.19	0.098	0.092	0.007	Uraniferous quartz-pebble conglomerate	coffinite, monazite	phosphates	14,631	1489	284	29	149	15
CAN	Hoidas Lake	2.8	2.4	0.068	0.065	0.002	vein-type	monazite, apatite	phosphates	11,319	1244	4042	444	166	18

(continued on next page)

Table A2 *(continued)*

Region-Country	Deposit	Resource data					Geology data			Financial data					
		(Mt)	**grade TREO (wt%)**	**TREO (Mt)**	**TLREO (Mt)**	**THREO (Mt)**	**Deposit type description$^{1)}$**	**REE-minerals$^{2)}$**	**Main REE mineral types$^{2)}$**	IGV (2011) (MUSD)	IGV (2015) (MUSD)	Value pt (2011) (USD)	Value pt (2015) (USD)	BP (2011) (USD/ Kg)	BP (2015) (USD/ Kg)
CAN	Foxtrot	14.4	1.01	0.146	0.116	0.030	peralkaline complex	fergusonite, allanite, chevkinite	silicates	26,742	3087	1857	214	183	21
CAN	Kipawa	27.1	0.4	0.107	0.068	0.039	peralkali and alkali syenite and granite complex	eudialyte, mosandrite	silicates	22,848	2730	843	101	214	26
CAN	Clay-Howells	8.5	0.73	0.062	0.056	0.006	hydrothermal fault-alteration breccias	monazite, (Ce-La-Ca) silicate, fergusonite, allanite, apatite	silicates	11,137	1197	1310	141	180	19
CAN	Two Tom	40.6	1.18	0.480	0.450	0.030	peralkaline complex	monazite, cerium-calcium silicates	silicates	75,214	7731	1853	190	157	16
CAN	Nechalacho (Thor Lake)	303.4	1.4	4.152	3.541	0.612	alkaline magmatism	allanite, monazite, bastnaesite, synchysite	silicates	794,357	93,729	2618	309	191	23
CAN	Strange Lake	492.5	0.9	4.406	2.763	1.655	A-type granitic peralkaline complex	arfvedsonite	silicates	925,642	109,989	1879	223	210	25
CAN	Ashram	249.1	1.9	4.700	4.509	0.190	carbonatite intrusive complex	monazite, xenotime, bastnasite	carbonates	749,657	75,372	3009	303	160	16
CAN	Lavergne-Springer	16.9	1.16	0.197	0.187	0.009	granitoid hostrock intruded by carbonatite	synchysite	carbonates	30,692	3034	1816	180	156	15
CAN	Niobec	1058.6	1.73	18.363	18.039	0.318	alkaline intrusive complex, with carbonatite core	bastnasite, monazite, apatite,	carbonates	2,868,467	297,054	2710	281	156	16
CAN	Montviel	250.6	1.45	3.645	3.584	0.060	carbonatite complex with alkaline intrusion	bastnasite, synchysite	carbonates	545,794	53,968	2178	215	150	15
	Buckton	3930.2	0.03	1.002	0.752	0.236	polymetallic black-shale	?	?	196,339	23,100	50	6	196	23
CAN	Grande-Vallée	1209.6	0.05	0.606	0.496	0.121	shale-clay deposit	?	?	105,610	11,890	87	10	174	20
CAN	Eco Ridge	59.3	0.16	0.093	0.084	0.009	?	?	?	14,115	1455	238	25	152	16
USA	Round Top	905.9	0.06	0.573	0.145	0.417	rhyolite laccoliths	yttrofluorite, yttrocerite, bastnasite, xenotime	phosphates	128,393	15,278	142	17	224	27
USA	Bokan	4.9	0.61	0.030	0.018	0.012	peralkaline granite intrusion	allanite, xenotime, monazite	silicates	6968	851	1422	174	232	28
USA	La Paz	128.2	0.04	0.056	0.045	0.009	hydrothermal mineralized quartz-feldspar gneisses	allanite, monazite	silicates	9465	1063	74	8	169	19
USA	Mountain Pass	31.6	6.57	2.072	2.063	0.012	carbonatite intruded into gneiss	bastnasite	carbonates	272,754	23,392	8631	740	132	11
USA	Bear Lodge	52.1	2.71	1.410	1.351	0.058	carbonatite and silico-carbonatite intrusive complex	ancylite, bastnaesite	carbonates	233,348	23,910	4479	459	165	17
Africa-ZAF	Steenkampskraal	0.7	14	0.093	0.090	0.008	intrusive to vein style	monazite	phosphates	15,778	1759	22,540	2513	170	19
Africa-ZAF	Zandkopsdrift	42.5	2.23	0.948	0.874	0.074	carbonatite/alkaline magmatic complex	monzanite, crandallite	phosphates	160,449	16,391	3775	386	169	17
Africa-KEN	Mrima Hill	159.4	3.86	6.145	5.588	0.558	carbonatite complex	monazite, gorceixite	phosphates	1,048,685	106,839	6579	670	171	17
Africa-MDG	Tantalus	435	0.08	0.355	0.291	0.070	peralkaline and regolith-hosted	fasibitikite, chevkinite, eudialyte,	silicates	63,166	7186	145	17	178	20

(continued on next page)

Table A2 *(continued)*

Region-Country	Deposit	Resource data					Geology data			Financial data					
		(Mt)	grade TREO (wt%)	TREO (Mt)	TLREO (Mt)	THREO (Mt)	Deposit type description[1)]	REE-minerals[2)]	Main REE mineral types[2)]	IGV (2011) (MUSD)	IGV (2015) (MUSD)	Value pt (2011) (USD)	Value pt (2015) (USD)	BP (2011) (USD/Kg)	BP (2015) (USD/Kg)
Africa-ZAF	Glenover	10.4	2.13	0.221	0.206	0.015	carbonatite complex	monazite, ionic clay apatite, monazite, synchysite, aeschynite	phosphates	42,080	4760	4046	458	190	22
Africa-MWI	Kangankunde	2.5	4.24	0.107	0.105	0.001	carbonatite complex	monazite, apatite, xenotime, bastnasite, daqingshanite	carbonates	14,681	1350	5872	540	137	13
Africa-MWI	Songwe Hill	31.8	1.48	0.657	0.436	0.034	carbonatite complex	synchysite, apatite	carbonates	79,072	8165	2487	257	120	12
Africa-NAM	Lofdal	1.7	0.59	0.010	0.001	0.009	carbonatite complex	xenotime, aeschnyite, bastnasite, yttrosynchysite	phosphates	3249	397	1911	233	325	40
Africa-TZA	Ngualla	41.7	4.19	1.748	1.715	0.034	carbonatite complex intruded into gneisses	bastnasite	carbonates	261,353	25,480	6267	611	150	15
Africa-TZA	Wigu Hill Twiga	0.5	5.27	0.025	0.026	0.000	carbonatite complex	bastnasite, monazite, synchysite, parasite, goyazite	carbonates	3261	239	6522	479	130	10
Africa-MOZ	Xiluvo	1.1	2.03	0.023	0.021	0.002	carbonatite complex	?	?	3755	391	3414	356	163	17
GRL	Kvanefjeld	956.3	1.08	10.320	9.094	1.218	alkaline intrusive complex	steenstrupine, lovozerite, eudialyte, vitusite, arfvedsonite	silicates	1,592,170	157,590	1665	165	154	15
GRL	Kringlerne	4300	0.65	28.058	19.307	8.815	alkaline intrusion	eudialyte, arfvedsonite	silicates	5,641,600	640,335	1312	149	201	23
GRL	Sarfartoq	8.3	1.72	0.143	0.140	0.003	carbonatite complex	bastnasite, synchysite, monazite	carbonates	22,233	2325	2679	280	155	16
BRA	Araxá	28.3	4.21	1.190	1.159	0.032	carbonatite complex	phosphates	phosphates	174,271	16,179	6158	572	146	14
BRA	Serra Verde	412	0.16	0.469	0.503	0.152	alkaline granite	monazite, xenotime	phosphates	118,829	13,604	288	33	253	29
KGZ	Kutessay II	18	0.26	0.047	0.025	0.022	pipe shaped granophyr	monazite, xenotime, parasite, bastnasite, fluocerite, synchysite	phosphates	13,061	1735	726	96	278	37
SWE	Olserum	7.8	0.62	0.048	0.032	0.016	hydrothermally overprinted placer deposit	apatite, monazite, xenotime	phosphates	10,234	1250	1312	160	213	26
SWE	Norra Kärr	58.1	0.59	0.343	0.171	0.173	peralkaline nepheline-syenite complex	eudialyte	silicates	80,366	9549	1383	164	234	28
TUR	Aksu Diamas	494	0.07	0.345	0.311	0.030	tuffaceous placer deposits	allanite, chevkinite, apatite, titanite	silicates	52,626	5377	107	11	153	16
GER	Storkwitz	4.5	0.45	0.020	0.020	0.001	carbonatite complex	?	?	2989	295	664	65	149	15
Total:										17,189,867	1,853,070				

Source for resource data: TMR (2015). Details for REO grade of the resources for individual REO are documented Table A1. expl.: Exploration Project. TREO: Total Rare Earth Oxides. TLREO: Total Light Rare Earth Oxides (La_2O_3; CeO_2; Pr_6O_{11}; Nd_2O_3; Sm_2O_3); THREO: Total Heavy Rare Earth Oxides (Eu_2O_3; Gd_2O_3; Tb_4O_7; Dy_2O_3; Ho_2O_3; Er_2O_3; Tm_2O_3; Yb_2O_3; Lu_2O_3; Y_2O_3).

[1)]: Deposit type description according to information provided in company reporting. [2)]: Mineralogical information regarding the REE resource was obtained from company information and is highly variable in terms of details between different projects. The order of the listing does not imply relative abundance. Main REE mineral types (phosphates, silicates or carbonates) are inferred from the deposit description.

IGV: In-ground value has been calculated from resource data (Table A1) and price information for 2011 and 2015 (Table 1) as outlined in the Section 2 (data and methods). Value pt: Value per tonne of the resource. BP: Basket price for 1 kg of TREO contained in the resource. All financial data are non-debased; i.e., assuming 100% recovery.

Table A3
Valuation of REE companies; 2011–2015.

Company	Project (s)	Project Country	Ticker Symbol (s)	currency	peak share price 2011	2011 #shares (million)	2011 MCAP (MUSD)	share price spring 2015	2015 #shares (milion)	2015 MCAP (MUSD)
Alkane Resources Ltd.	Dubbo Zirconia Project	AUS	ASX:ALK, OTCQX: ANLKY	AUD	2.24	269	623	0.38	414	118.4
Arafura Resources Ltd.	Nolans	AUS	ASX:ARU, PK: ARAFF	AUD	1.4	368	533	0.05	441	16.6
Crossland Strategic Metals Ltd.	Charley Creek (JV)	AUS	ASX:CUX	AUD	0.24	137	34	0.01	300	2.3
GBM Resources Ltd.	Milo	AUS	ASX:GBZ	AUD	0.12	170	21	0.02	485	7.3
Greenland Minerals and Energy Ltd.	Kvanefjeld	GRL	ASX:GGG	AUD	1.33	404	556	0.07	669	35.2
Hastings Rare Metals Limited	Hastings	AUS	ASX:HAS	AUD	0.38	59	23	0.07	384	20.2
Lynas Corporation Ltd.	Mount Weld, Kangankunde	AUS	ASX:LYC	AUD	2.55	1714	4518	0.06	3371	152.1
Navigator Resources Limited	Cummins Range	AUS	ASX:NAV	AUD	0.14	466	67	0.02	18	0.2
Northern Minerals Limited	Browns Range	AUS	ASX:NTU	AUD	0.82	174	148	0.21	432	68.2
Peak Resources Ltd.	Ngualla	TZA	ASX:PEK	AUD	0.92	20	19	0.08	334	20.1
Canada Rare Earth Corp.	Clay-Howells, Lavergne-Springer, Two Tom	CAN	TSX.V:LL	CAD	0.43	81	35	0.03	143	3.4
Commerce Resources Corp.	Ashram	CAN	TSX.V:CCE	CAD	0.83	178	150	0.16	216	27.1
DNI Metals Inc.	Buckton	CAN	TSX.V:DNI	CAD	3.5	38	134	0.14	19	2.1
Frontier Rare Earths Ltd.	Zandkopsdrift (JV)	ZAF	TSX:FRO, PK: FREFF	CAD	3.38	90	306	0.16	90	11.2
Geomega Resources Inc.	Montviel	CAN	TSX.V:GMA	CAD	4.75	17	80	0.17	57	7.6
Great Western Minerals Group Ltd.	Steenkampskraal, Hoidas Lake	ZAF, CAN	TSX.V:GWG, OTCQX:GWMGF	CAD	1.06	356	381	0.05	419	16.4
Hudson Resources Inc.	Sarfartoq	GRL	TSX.V:HUD, OTCQX:HUDRF	CAD	1.77	62	111	0.23	81	14.7
Matamec Explorations Inc.	Kipawa	CAN	TSX.V:MAT, OTCQX:MHREF	CAD	0.63	116	74	0.05	137	5.4
MBAC Fertilizer Corp.	Araxá	BRA	TSX:MBC, OTCQX: MBCFF	CAD	3.26	86	285	0.05	118	4.6
Mkango Resources Ltd.	Songwe Hill	MWI	TSX.V:MKA	CAD	0.97	37	37	0.10	73	5.7
Montero Mining and Exploration Ltd.	Wigu Hill Twiga	TZA	TSX.V:MON	CAD	0.83	42	36	0.01	71	0.6
Namibia Rare Earths Inc.	Lofdal	NAM	TSX:NRE	CAD	0.78	42	33	0.19	78	11.6
Orbite Aluminae Inc.	Grande-Vallée	CAN	TSX:ORT, OTCQX: EORBF	CAD	5.45	120	661	0.30	321	75.3
Pacific Wildcat Resources Corp.	Mrima Hill	KEN	TSX.V:PAW	CAD	1.73	109	191	0.03	295	6.9
Pancontinental Uranium Corporation	Charley Creek (JV)	AUS	TSX.V:PUC	CAD	0.43	55	24	0.03	83	1.9
Pele Mountain Resources Inc.	Eco Ridge	CAN	TSX.V:GEM, OTCQX:GOLDF	CAD	0.61	134	83	0.04	179	5.6
Quest Rare Minerals Ltd.	Strange Lake Enriched	CAN	TSX:QRM, MKT: QRM	CAD	8.32	54	450	0.17	68	9.0
Rare Element Resources Ltd.	Bear Lodge	USA	TSX:RES, MKT: REE	CAD	13.62	44	603	1.00	48	37.4
Search Minerals Inc.	Foxtrot	CAN	TSX.V:SMY	CAD	0.66	47	31	0.04	116	3.6
Stans Energy Corp.	Kutessay II	KGZ	TSX.V:HRE, OTCQX:HREEF	CAD	3.2	152	493	0.10	157	12.3
Tasman Metals Ltd.	Norra Kärr, Olserum	SWE	TSX.V:TSM	CAD	4.7	58	274	0.73	66	37.8
Ucore Rare Metals Inc.	Bokan	USA	TSX.V:UCU, OTCQX:UURAF	CAD	1.11	149	167	0.27	198	41.8
Avalon Rare Metals Inc.	Nechalacho	CAN	TSX:AVL	USD	9.45	94	1421	0.31	137	65

(continued on next page)

Table A3 *(continued)*

Company	Project (s)	Project Country	Ticker Symbol (s)	currency	peak share price 2011	2011 #shares (million)	2011 MCAP (MUSD)	share price spring 2015	2015 #shares (milion)	2015 MCAP (MUSD)
Molycorp Inc.	Mountain Pass	USA	NYSE:MCP	USD	77.54	82	10,235	0.92	245	344
Texas Rare Earth Resources Corp.	Round Top	USA	OTCQX:TRER	USD	9	28	399	0.20	37	11
Galileo Resources PLC;.	Glenover (JV)	ZAF	AIM:GLR	GBP	0.48	102	49	0.02	125	3
Tantalus Rare Earths AG	Tantalus	MDG	F:TAE:GR	Euro	not listed in 2011			10.50	3	33
AMR Mineral Metal Inc.	Aksu Diamas	TUR	not listed							
Promac Lda.	Xiluvo	MOZ	not listed							
Rimbal Pty Ltd	TANBREEZ	GRL	not listed							
Seltenerden Storkwitz AG	Storkwitz	GER	not listed							
Mining Ventures Brasil Ltda.	Serra Verde	BRA	not listed							
Appia Energy Corp.	Elliott Lake Teasdale	CAN	not listed							
Fer-Min-Ore (Pty) Ltd.	Glenover (JV)	ZAF	not listed							
						TOTAL	23,285			1206

Data sources: company web sites and www.reuters.com/finance/stocks for share price information and shares outstanding spring 2015 (data collected between 25 and 27 February 2015). Shares outstanding in 2011 from company annual reports and ww.sedar.com. Market captialization is calculated from share price and shares outstanding data. Annual average exchange rates for conversion to USD are: AUD 2011: 1.0338; 2015: 0.7521; CAD 2011: 1.0114; 2015: 0.7829; GBP 2011: 1.6041; 2015: 1.5285. (from: http://www.usforex.com/forex-tools/historical-rate-tools/yearly-average-rates).

#shares: Number of shares outstainding; MCAP: Market capitalization (here: share price*shares outstanding; disregaring any possible assets of the companies).

References

Adamas Intelligence, 2016. Rare Earth Market Outlook Update: Supply, Demand, and Pricing from 2016 through 2025. Castilloux, R., (Ed.).

Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., Kirchain, R.E., 2012. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ. Sci. Technol. 46, 3406–3414.

Barteková, E., Kemp, R., 2016. National strategies for securing a stable supply of rare earths in different world regions. Res. Pol. 49, 153–164.

BGR, 2016. Bundesanstalt für Geowissenschaften und Rohstoffe – Federal Institute for Geosciences and Natural Resources - Preismonitor, ⟨http://www.deutsche-rohstoffagentur.de/DERA/DE/Rohstoffinformationen/Rohstoffpreise/Preismonitor/preismonitor_node.html⟩. (Accessed 15 May 2016.

Binnemans, K., Jones, P.T., Van Acker, K., Blanpain, B., Mishra, B., Apelian, D., 2013. Rare-Earth economics: the balance problem. JOM 65 (7), 846–848.

Binnemans, K., Jones, P.T., 2015. Rare Earths and the balance problem. J. Sustain. Metall. 1, 29–38.

Bloomberg, 2015. Rare earth prices. ⟨www.bloomberg.com⟩ (Accessed 01 Feb 2015).

Bogner, S., 2015. The REE basket price deception and the clarity of OPEX. Rockstone Research Ltd., Rare Earth Elements #9. ⟨http://rockstone-research.com/images/Commerce9EN.pdf⟩. (Accessed: 15 May 2016).

Buijs, B., Sievers, H., 2012. Critical Thinking about Critical Minerals: Assessing risks related to resource security. POLINARES working paper n. 33, March 2012. ⟨http://www.polinares.eu/docs/d2-1/polinares_wp2_annex1a.pdf⟩ (Accessed 12 August 2016).

Campbell, G.A., 2014. Rare earth metals: a strategic concern. Miner. Econ. 27, 21–31. http://dx.doi.org/10.1007/s13563-014-0043-y.

Chakhmouradian, A.R., Wall, F., 2012. Rare Earth elements. Elements 8 (5), 321–400.

Chen, Z., 2011. Global rare earth resources and scenarios of future rare earth industry. J. Rare Earth 29 (1), 1–6.

Du, X., Graedel, T.E., 2013. Uncovering the end uses of the rare earth elements. Sci. Total Environ. 461–462, 781–784.

EURARE, 2012. Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits. Seventh framework programme. ⟨http://www.eurare.eu/⟩ (Accessed 10 August 2016).

EURARE, 2015a. News. Presentation by GME Ltd. 'EURARE Kvanefjeld Refinery Demo Plant Work Package 5′, October 2015. ⟨http://eurare.eu/docs/20151023_KrebsD_EURAREKvanefjeldRefineryDemoPlant.pdf⟩ (Accessed 12 August 2016).

EURARE, 2015bNews release, Tasman Metals Ltd. ⟨http://www.tasmanmetals.com/s/NewsReleases.asp?ReportID=732082 & _Type=News-Releases & _Title=TasmanCompletes-Magnetic-Separation-Pilot-Plant-For-The-Norra-Karr-Heavy-R⟩ (Accessed 12 August 2016).

ERECON, 2014. Strengthening the European rare earths supply chain: Challenges and policy options. Kooroshy, J., Tiess, G., Tukker, A., Walton, A., (eds.).

Ernst and Young, 2011. Technology minerals. The rare earth race is on! April 2011. ⟨http://institut-seltene-erden.org/wpcontent/uploads/2012/03/Ernstyoung-REE1.pdf⟩ (Accessed 12 August 2016).

Falconnet, P., 1985. The economics of rare earths. J. Less Common Met. 111 (1), 9–15.

GME Ltd, 2015. New Memorandum of Understanding Signed With NFC to Focus on the Development of the Kvanefjeld Project. ⟨http://www.ggg.gl/docs/ASX-announcements/australian-public-company-GGG-Signed-MOU-With-NFCto-Focus-on-the-Development-of-the-Kvanefjeld-Project-in-Greenland.pdf⟩ (Accessed 12 August 2016).

Goodenough, K.M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E.A., Sadeghi, M., Schiellerup, H., Müller, A., Bertrand, G., Arvanitidis, N., Eliopoulos, D.G., Shaw, R.A., Thrane, K., Keulen, N., 2016. Europe's rare earth element resource potential: an overview of REE metallogenic provinces and their geodynamic setting. Ore Geol. Rev. 71 (1), 838–856.

Hatch, G.P., 2012. Dynamics in the global market for rare earths. Elements 8 (5), 341–346.

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

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

Jaireth, S., Hoatson, D.M., Miezitis, Y., 2014. Geological setting and resources of the major rare-earth-element deposits in Australia. Ore Geol. Rev. 62, 72–128.

Jenkin, G.R.T., Lusty, P.A.J., MacDonald, I., Smith, M.P., Boyce, A.J., Wilkinson, J.J., 2015. Ore Deposits in an Evolving Earth 393. Geological Society, London, 265–276. http://dx.doi.org/10.1144/SP393.13, Special Publications.

JORC, 2012. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. ⟨http://www.jorc.org/docs/JORC_code_2012.pdf⟩ (Accessed 07 August 2016) .

Jordens, A., Cheng, Y.P., Waters, K.E., 2013. A review of the beneficiation of rare earth element bearing minerals. Miner. Eng. 41, 97–114.

Kanazawa, Y., Kamitani, M., 2006. Rare earth minerals and resources in the world. J. Alloy Compd. 408–412, 13391343.

Kirchner, S., 2014. Regulating Foreign Direct Investment in Australia. Financial Services Institute of Australasia (Finsia), Sydney.

Linnen, R.L., Samson, I.M., Williams-Jones, A.E., Chakhmouradian, A.R., 2014. Geochemistry of the Rare Earth Element,Nb, Ta, Hf, and Zr deposits. In: Treatise on Geochemistrysecond ed.. Elsevier.

Liu, H., 2016. Rare Earths: Shades of grey. Can China continue to fuel our clobal clean & smart Future? China Water Risk, Report, pp. 63.

Machacek, E., Fold, N., 2014. Alternative value chains for rare earths: the Anglo-deposit developers. Res. Pol. 42, 53–64.

Majury, N., 2013. 'Trusting the numbers': mineral prospecting, raising finance and the governance of knowledge. Trans. Inst. Br. Geogr. R Geogr Soc. 39, 545–558. http://dx.doi.org/10.1111/tran.12044.

Mancheri, N., Sundaresan, L, Chandrashekar, S., 2013. Dominating the World. China and the Rare Earth Industry. International Strategic and Security Studies Programme, National Institute of Advanced Studies, Bangalore.

Mancheri, N., A., 2015. World trade in rare earths, Chinese export restrictions, and implications. Res. Pol. 46, 262–271.

Massari, S., Ruberti, M., 2013. Rare earth elements as critical raw materials: focus on international markets and future strategies. Res. Pol. 38 (1), 36–43.

Mining Journal, 2016. China REE industry squeezed. Issue 12–25. 2016, p. 3.

Packey, D.J., Kingsnorth, D., 2016. The impact of unregulated ionic clay rare earth mining in China. Res. Pol. 48, 112116.

Polinares, 2012. EU Policy on Natural Resources. ⟨http://www.polinares.eu/⟩ (Accessed 14 August 2016).

Roskill, 2011. Rare Earths & Yttrium: Market Outlook to 2015, 14th ed. Roskill Information Services Ltd., London.

Schlinkert, D., van den Boogaart, K.G., 2015. The development of the market for rare earth elements: insights from economic theory. Res. Pol. 46, 272–280.

Schodde, R., 2015. Updated report on the importance of junior exploration companies to the NSW mining industry. MinEx Consulting Pty Ltd., prepared for the NSW Department of Trade & Investment, pp. 40.

Schüler, D., Buchert, M., Liu, R., Dittrich, S., Merz, C., 2011. Study on Rare Earths and Their Recycling. Final Report for The Greens/EFA Group in the European Parliament. Öko-Institut e.V., Darmstadt, Germany.

Sedar, 2015. ⟨www.sedar.com⟩. (Accessed 03 Feb 2015) .

SNL Metals and Mining, 2015. Estimated Global Nonferrous Exploration Budget Total. ⟨go.snl.com/rs/snlfinanciallc/images/World-Exploration-Trends-WET-Report-2015-English-USletter.pdf⟩. (Accessed 14 August 2016).

Taylor, S.R., McClennan, S.M., 1985. The Continental Crust: its Composition and Evolution. Blackwell Scientific Publications, Oxford.

TMR, 2015. TMR Advanced Rare-Earth Projects Index. ⟨www.rareearths.org⟩ (last Accessed 14 June 15).

Tse, P.K., 2011. China's Rare Earth Industry. U.S. Dept. of the Interior; USGS. Open-File Report 2011–1042. ⟨https://pubs.usgs.gov/of/2011/1042/of2011-1042.pdf⟩ (Accessed 14 August 2016).

USGS, 2011. Mineral Commodity Summaries 2011. ⟨http://minerals.usgs.gov/minerals/pubs/mcs/2011/mcs2011.pdf⟩ (Accessed 14 August 2016).

USGS, 2016a. Mineral commodity summaries 2016: U.S. Geological Survey, pp. 202. http://dx.doi.org/10.3133/70140094.

USGS, 2016b. Minerals Information. Rare Earths. Statistics and Information. ⟨http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/⟩ (Accessed 14 August 2016).

Wall, F., 2014. Rare Earth Elements. Critical Metals Handbook first ed.. John Wiley and Sons, Ltd..

Weng, Z., Jowitt, S.M., Mudd, G.M., Haque, N., 2015. A detailed assessment of global rare earth element resources: opportunities and challenges. Econ. Geol. 110, 1925–1952.

Wübbeke, J., 2013. Rare earth elements in China: policies and narratives of reinventing an industry. Res. Pol. 38, 384–394.

Zhü, K., Zhao, S., Yang, S., Liang, C., Gu, D., 2016. Where is the way for rare earth industry in China: an analysis via ANP-SWOT approach. Res. Pol. 49, 349–357.