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# 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

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A B S T R A C T

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).

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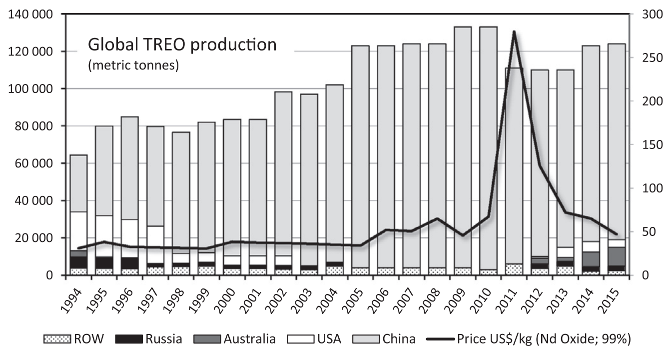


**Fig. 1.** Global annual production of Rare Earth Oxides (REO). Production has doubled from 1994 (65,000 t) to about 130,000 t in 2010, and about 120,000 t (with an official Chinese domestic production quota of 105,000 t, and production outside Chine) in recent years. During the same time, the supply 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).

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