Economic geology of rare-earth elements in 2014: a global perspective

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The rare-earth element (REE) market is still dominated by China, which currently has a share in global REE mine production of about 80 %, down from about 95 % in 2011. This percentage will decrease further over the coming years, with the two large carbonatite-related REE deposits of Mountain Pass (USA) and Mount Weld (Australia) coming to full production. These two high-grade open pit mines (both with about 8 % rare earth oxides) will add capacity to the global REE supply of about 50 %, and they are the reference points for any economic evaluation of other REE development projects. Only very few of the more than 200 REE exploration projects around the world will be able to survive in an increasingly competitive market.

Le marché des éléments rares (REE) est toujours dominé par la Chine qui, actuellement, produit 80% des REE, en diminution depuis 2011 (sa part était égale à 95%). Ce pourcentage va continuer à décroître dans les années à venir, en tenant compte des deux vastes gisements de terres rares associés à des carbonatites, de Mountain Pass (USA) et de Mount Weld (Australie), arrivant à un état de pleine production. Ces deux exploitations à ciel ouvert d'un minerai riche (contenant chacun de l'ordre de 8% d'oxydes de terres rares), vont augmenter la production globale de REE d'environ 50% et constituent une référence pour toute évaluation économique d'autres projets de développement des REE. Seul un très petit nombre parmi plus de 200 projets d'exploration dans le monde sera capable de survivre à un marché de plus en plus compétitif.

El mercado de elementos de las tierras raras (REE) sigue dominado por China, que actualmente tiene una participación en la producción mundial de alrededor del 80%, frente al estimado 95% en el 2011. Este porcentaje se reducirá aún más en los próximos años, con los dos grandes explotaciones de carbonatitas con depósitos de tierras raras, REE, que estan llegando a la plena producción, en Mountain Pass (EE.UU.) y Mount Weld (Australia). Estas dos minas a cielo abierto que tienen un alto grado de mineral (ambos con alrededor del 8% de óxidos de tierras raras) añadirán capacidad de oferta mundial en REE de alrededor del 50%, y son puntos de referencia para la evaluación económica del desarrollo de otros proyectos de REE. Sólo unos pocos de los más de 200 proyectos de exploración de REE en todo el mundo serán capaces de sobrevivir en un mercado cada vez más competitivo.

There was a time, only about three years ago, when the western world suddenly became alarmed that China was going to crush the high-tech sector of western economies due to its dominance in rare-earth-element (REE) mining and processing. China then had a share of 95 % of the global REE production and began to impose export restrictions. Prices rose dramatically in 2011, for some REEs up to a hundredfold. It appeared that Deng Xiaoping's famous strategic forecast "The Middle East has oil - China has rare earths" would become true.

However, the alarm was short-lived. The elevated REE prices were the incentive for a multitude of exploration and development projects around the globe. It turned out that rare earths are not as rare as their name would suggest. The Chinese share of rare-earth production now stands at about 80 % of the world market (***Fig. 1***), and several new projects outside China will add additional REE production in the coming years. Prices in 2012 were half of their 2011 peak, and half again in 2013. The price range expected for the coming years is about 2.5 times the pre-2010 prices, which had been relatively static for many years and drove all non-Chinese competitors out of the market. There is now fear of oversupply, given the discovery of several large and high-grade REE deposits outside of China. Only a few major low-cost REE mine projects will survive out of the more than 200 REE exploration projects of recent years. This report aims to delineate some main features of the economic geology of the rare-earth elements with a perspective for the coming years.

Economic background and geology

Rare-earth elements are the 15 lanthanide metals at the bottom of the periodic table, from lanthanum (atomic number 57) to lutetium (71), plus the chemically similar metals scandium (21) and yttrium (39) (***Fig. 2***). Some of these elements are exceptionally useful for high-tech applications such as supermagnets, lasers, solar panels, and advanced catalysts. Much of the industrial potential of these "modern" metals is still in the research stage, and demand for particular REEs is dynamic and may quickly change with technological progress. Some of the REEs are common

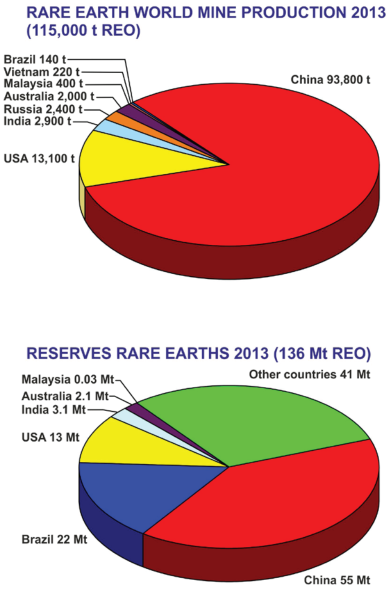

Figure 1: REE world mine production (top) and reserves (bottom) based on information from the U.S. Geological Survey (USGS, Mineral Commodity Summaries, Rare earths, February 2014). The USGS definition of reserves includes here what is internationally known as resources. REE resources are very large relative to current and expected future demand and are increasing with current exploration.

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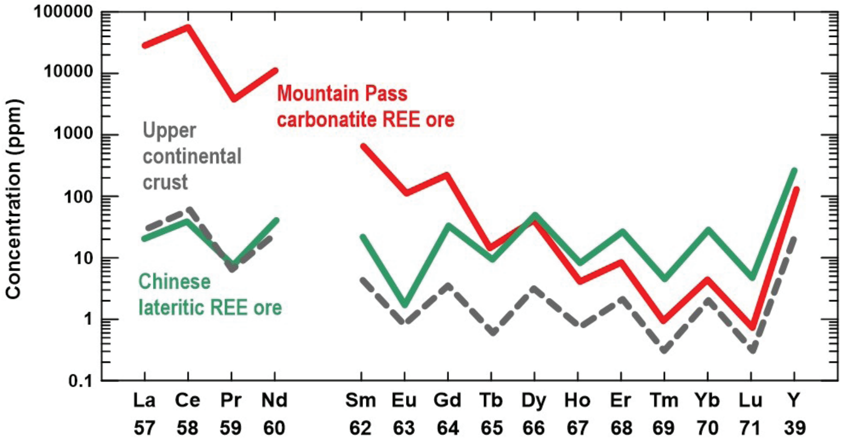

Figure 2: Abundance patterns of the rare-earth elements in the average upper continental crust and in two representative REE ore types, i.e. high-grade carbonatite ore from Mountain Pass, USA, and lateritic ion-adsorption ore from southern China. The gap at atomic number 61 is due to the fact that promethium has no long-lived or stable isotopes and does not occur in natural materials. From Haxel et al. *(2002).*

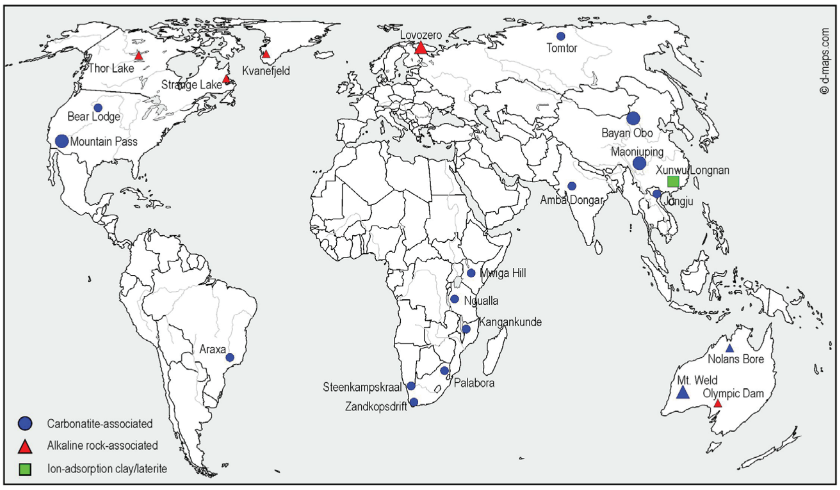

Figure 3: Major REE mines (larger symbols) and exploration/development projects (smaller symbols). Current REE production is mainly from China (Bayan Obo and Maoniuping, as well as many smaller deposits working on lateritic weathering crusts) and from Mountain Pass in the USA. The Mount Weld deposit in western Australia is scheduled to produce 11,000 t REO in 2014. Several mines in the Lovozero district (Russia) on the Kola Peninsula produce about 1000 t REO/year as by-product of niobium-titanium mining.

in the Earth's crust, i.e. comparable in abundance to the base metals copper, zinc, or nickel, with a few tens of g/t (=ppm). These are the light REEs (atomic numbers 57-63; LREE) such as lanthanum, cerium and neodymium. Some of the heavy REEs (atomic numbers 64-71; HREE) such as terbium or lutetium, but also europium, have abundances around 1 g/t, which is similar to tungsten or bismuth, but still orders of magnitude more than gold or platinum.

The prices of individual REEs are very variable and depend on both geological availability and technological demand. The group of REEs always occurs together in ore deposits, but in a specific mix for each deposit, and cannot be mined separately. This situation of "coupled elements" (Wellmer 2008) leads to an imbalance between the proportion of different REEs produced and that required by the market. There are one or a few elements in high demand (and consequently high-priced) which drive REE production. Such "drivers" are europium and terbium, used for phosphors in video screens and LEDs, and neodymium together with praseodymium and dysprosium in permanent magnets. Other REEs are relatively cheap, but technological progress may quickly modify the demand structure. The market value of the global 2013 REE mine production of approximately 115,000 t REO (grade and production of REEs are usually given as rare-earth-element oxides in the mining industry) is about 3-4 billion USD, which is orders of magnitude less than that of iron ore or copper. Most of this value comes from the processing of the ore, i.e. separation and purification of the individual metals or metal oxides, which is difficult due to the chemical similarity of the REEs. The mining cost of the ore is only about 5 % of the total production cost. This is different to most other raw materials.

In terms of value, neodymium and praseodymium dominate the global REE market, with 1.9 billion USD (23,000 t) combined. These two metals are mainly used for $Nd_2Fe_{14}B$ permanent magnets, and demand is forecast to grow at 10 % per annum, driven by the wind turbine, automobile and personal electronics sectors. Rare earth magnets are significantly stronger and have greater temperature resistance than conventional ferrite magnets. The next important market by value is phosphors (light-emitting electrodes) in which europium and terbium are mainly used (about 600 t @ 680 M USD). The big-volume elements lanthanum and cerium represent the largest share in the REE market in terms of tonnage (about 72,000 t @ 550 M USD); they are mainly used in nickel-metal-hydride batteries, super-alloys, and as catalysts for pollution control and refining of oil. There are a number of emergent markets, such as LREE polybutadiene rubber for "green" tyres with less road resistance, i.e. lower fuel consumption, and many more.

REE deposit types

The major REE mines are related to carbonatite intrusions (***Fig. 3***). REE mineralisation can be part of a magmatic intrusion, such as at Mountain Pass, USA; or it can be part of a carbonatite-associated hydrothermal system, such as at Bayan Obo, China; or it can be part of the laterite profile above a carbonatite intrusion (supergene enrichment), such as at Mount Weld, Australia, or Ngualla, Tanzania, with pristine low-grade REE mineralised carbonatite below. The carbonatite-related REE deposits are all strongly dominated by LREEs (***Fig. 2***) concentrated in the two major REE minerals of bastnaesite [$REECO_3F$] and monazite [$REEPO_4$]. Nevertheless, each ore deposit has its individual mix of REEs and therefore a specific ore value. Tonnage-grade data for the major mines and prospects are compiled in ***Fig. 4***.

REE production from carbonatites started in the 1960s with the Mountain Pass deposit in California, which dominated the REE market until the mid 1980s, when it was replaced by the Bayan Obo mine in northern China, where REEs were (and are) a by-product of large-scale iron ore mining. The resources of Bayan Obo are estimated at 1.5 Gt @ 35 % Fe with part of the orebody at 5-6 % REO. The Mountain Pass mine was a world leader in REE production from 1965 until 1985, when the cheap Chinese REE production from Bayan Obo forced this mine to stand-by for more than twenty years. Mountain Pass came back to life in 2013 after a 1.4 billion USD investment in state-of-the-art mining and processing technology. Production in 2013 was 13,100 t REO with proceeds of 42.3 USD/kg Σ REE metal and oxide products, and production in 2014 is scheduled at 19,000 t REO. The Mountain Pass open-pit mine has reserves of 18 Mt (million tonnes) at an average ore grade of 8 % REO (cut-off grade of 5 % REO), but a much larger resource. The Mount Weld project in western Australia has reserves of 24 Mt at an average ore grade of 7.9 % REO. The open pit was scheduled to operate with a cut-off grade of 2.5 % REO, but the cut-off is now revised to 4-7 % REO given the still decreasing world market prices for REEs.

Alkaline rocks host another type of mineralogically more complex REE mineralisation which has elevated contents of HREEs. These deposits usually are polymetallic and also carry mineralisation of Nb, Zr, Hf, Ti and U, but still need to prove their economic viability. A classical type example is the Lovozero district in the Kola alkaline province of NW Russia, with very large apatite and titanite deposits with current (Umbozero and Karnasurt mines) and planned (Alluaiv) REE by-production from loparite, a REE-bearing titanium-niobium oxide.

The Kvanefjeld REE-U-Zn deposit is in the Ilimaussaq alkaline complex of southwestern Greenland, which is similar to the alkaline rocks of the Kola Peninsula, and has a very exotic mineralogy. The Kvanefjeld deposit was explored since the 1970s for uranium, bound in the complex sodium-zirconium silicate of eudialyte, which carries elevated contents of U and REEs, together with other exotic minerals such as steenstrupine, a U-bearing Na-REE silicate-phosphate. The deposit is most valuable for its uranium resource with planned by-production of REEs and Zn (956 Mt @ 273 g/t U_3O_8, 1.1 % REO, 0.24 % Zn; at a cut-off grade of 150 g/t U_3O_8). However, although mining can be by open pit, REE recovery may be difficult and expensive, as for most alkaline rock-hosted REE deposits.

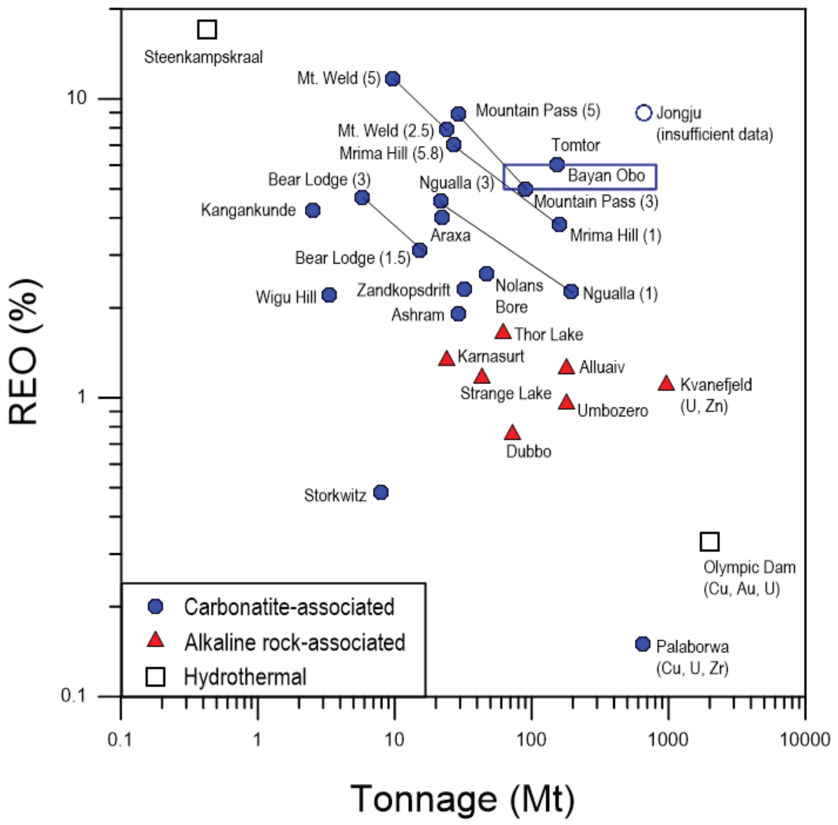

Figure 4: Tonnage-grade plot for major REE mines and exploration/development projects (for location see **Fig. 3***). Numbers in parenthesis for some deposits are cut-off grade in % REO. The large-tonnage deposits of Kvanefjeld (Greenland), Olympic Dam (Australia) and Palaborwa (South Africa) have REEs as possible by-products only. Resource data for the recently announced Jongju deposit in North Korea are currently insufficient, and the Tomtor (Russia) data are inferred resources only. The box for Bayan Obo (China) locates the various grade-tonnage estimates for this deposit. Ion-adsorption clay/weathering crust deposits from South China are not shown; individual deposits of this type are small and usually have grades around 0.1 % REO (with a dominance in HREEs and Y). The Storkwitz REE occurrence in Germany is shown for comparison; this carbonatite prospect is not only small and low grade but also at >600 m depth. Monazite placer deposits are not shown; they have a grade of <0.1 % REO. Base data from Orris and Grauch (2002), actualised and complemented by company information (Alkane Resources, Arafura Resources, Avalon Rare Metals, Commerce Resources, Frontier Rare Earths, Greenland Minerals, Lynas Corporation, Molycorp, Pacific Wildcat Resources, Peak Resources, Quest Resources, Rare Element Resources, Seltenerden Storkwitz), and Hoatson* et al. *(2011), Eilu (2012) and Elsner (2012). See the rare-earths blog at* http://www.techmetalsresearch.com *for updates and* in-situ *ore value based on proportion of REEs and actual REE prices ("basket price").*

Monazite is a common accessory mineral in all igneous rocks and can be concentrated in placer deposits together with other erosion-resistant heavy minerals such as ilmenite, zircon or cassiterite. Monazite-rich placers were an important source for REE production until the mid-1960s. Their grade is <0.1 % REO. There is currently a very minor REE by-production from titanium placer mining. The major problem of monazite mining is radioactivity due to elevated thorium content, which imposes a high cost for handling and disposal of radioactive material. However, if thorium should become an attractive raw material for thorium-based nuclear power, then monazite mining for both Th and REEs may become attractive again.

A particular type of REE deposits is lateritic weathering crusts over granitic terrain. Tropical/subtropical weathering leads to residual enrichment of REEs with preferential enrichment of HREEs and Y by adsorption to the clay fraction. This type of residual lateritic enrichment deposits has very low grade, commonly <0.1-0.3 % REO, and small tonnage, but is mined at many localities in South China due to its valuable HREE content (*Fig. 2*), and low investment cost. Mining, mostly in a semi-industrial way, is by acid leaching and produces serious environmental problems of which the local population and the Chinese government are now becoming aware.

A similar enrichment process by preferential adsorption of HREEs, but by iron-manganese oxides/hydroxides from seawater, is known from deep-sea nodules/crusts and sediments with very low clastic or biogenic input. Such REE-rich pelagic muds in the South Pacific have around 0.1 % REO, easily recoverable by dilute acid attack (Kato *et al.* 2011). Due to their vast extent, these oceanic muds hold enormous resources, although their recovery from 4,000-5,000 m water depth is currently illusionary.

A more accessible and very large REE resource is locked in apatite, which occurs both in magmatic and sedimentary phosphate deposits. The giant sedimentary phosphate deposits (annual world mine production of 224 Mt of phosphate rock in 2013, with Morocco and USA as major producers in the western world) have a few hundred ppm REEs on average, and magmatic-hydrothermal apatite deposits carry a few thousand ppm REE. There are innovative low-cost processing technologies currently in development to extract REEs from phosphoric acid and phosphogypsum which could strongly impact the REE market (Christmann 2014).

Conclusions

The decision by the Chinese government in 2011 to impose an export quota for REEs has made the public and policy-makers aware that some key industries in the western world are critically dependent on a secure supply of these "modern" metals. This is particularly true for electric power from wind turbines (a modern 3 MW wind turbine uses 300-600 kg Nd+Pr), automobiles (a conventional car has currently about 0.5 kg of REEs, and electric/hybrid cars need 20-30 kg of REEs), or for billions of smart phones and light-emitting phosphors (LEDs) with <1 g REE each.

The rare-earth metals are not rarer than the more familiar industrial base metals such as lead, zinc, copper, or tin. Their perceived rareness is a consequence of the apparent rareness of their occurrence in ore deposits, which is largely due to decades of low REE prices and consequent lack of exploration. The price hike in 2010/2011 induced a significant global exploration effort with the discovery of dozens of new REE deposits. For some applications, it also induced the substitution of REEs by other raw materials. Exploration and development success led to an increase in REE mine production outside China, concomitant with significant decreases in price. Several new mines will add REE mine capacity over the next few years. Only low-cost producers with high ore grade, favourable mineralogy, and know-how in complex processing technology will survive. Development of the giant Tomtor deposit in northern Siberia or confirmation of the recent reports on the apparently very-large and high-grade Jongju deposit in North Korea could markedly disturb the REE price structure.

There may be short-lived supply shortages (and corresponding price increases) for some specific REEs, but it can be expected that global reserves and resources of REEs are large enough to meet global demand for a very long time to come, even if high growth rates in demand should actually occur. The REE market of the last years has shown the effectiveness of the self-regulating "feedback control cycle" of mineral supply, i.e. increase in price triggers response both on the supply side (mine development, recycling) and in demand (substitution and new technologies) (Wellmer and Dalheimer 2012). In the past, a Chinese monopoly in REE production came about due to too low prices, even though REE resources are widespread over the globe. Now, however, the supply risk is decreasing due to a more geographically balanced mine production pattern, and this situation is expected to continue for the near future.

References

Christmann P (2014) A forward look into rare earth supply and demand: a role for sedimentary phosphate deposits? 2nd Intern Symp on "Innovation and Technology in the Phosphate Industry", *Procedia Engineering*, in print.

Eilu P (2012) *Mineral Deposits and Metallogeny of Fennoscandia*. Geological Survey of Finland, Special Paper 53: 1-401

Elsner H (2012) Das mineralische Rohstoffpotenzial der nordeuropäischen Arktis (Mineral Raw Material Potential of the Northern European Arctic). Hannover: DERA Rohstoffinformationen. *http://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-03.html*

Haxel GB, Hedrick JB, Orris GJ (2002) Rare earth elements - critical resources for high technology. U.S. Geological Survey Fact Sheet 087-02.

Hoatson DM, Jaireth S, Miezitis Y (2011) *The Major Rare-Earth-Element Deposits of Australia: Geological Setting, Exploration and Resources*. Canberra: Geoscience Australia.

Kato Y, Fujinaga K, Nakamura K, Takaya Y, Kitamura K, Ohta J, Toda R, Nakashima T, Iwamori H (2011) Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements. *Nature Geoscience* 4: 535-539. DOI:10.1038/ngeo1185

Orris GJ, Grauch RI (2002) Rare earth element mines, deposits, and occurrences. US Geol Survey Open-File Report 02-189: 1-174

Wellmer F-W (2008) Reserves and resources of the geosphere, terms so often misunderstood. Is the life index of reserves of natural resources a guide to the future? *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*159/4: 575-590. DOI: 10.1127/1860-1804/2008/0159-0575

Wellmer F-W, Dalheimer M (2012) The feedback cycle as regulator of past and future mineral supply. *Mineralium Deposita* 47: 713-729. DOI: 10.1007/s00126-012-0437-0