

Rare Earths – Aspects of Market and Beneficiation

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Although varying definitions exist, it is widely viewed that the Rare Earth Elements (REEs) are a group of elements of the periodic table of elements (PSE) comprised of the 15 lanthanides and yttrium, although scandium is occasionally included. They are high-tech-metals of great economic importance and dynamically growing demand, especially with respect to the permanent magnet industry. Although usually grouped collectively as one commodity and market, each individual REE is unique and this often extends to its end-use, and therefore its end-market(s). For example, the REEs that serve the glass polishing or auto catalyst industry are not the same as those that dominantly serve the magnet industry. Therefore, the supply-demand profile of each REE is unique, with some forecasted to remain in surplus (e.g. La, Ce, Y), and others that are forecasted to remain in deficit for several years (e.g. Pr, Nd). REE-ores

feature several special characteristics in terms of mineralogy and genesis that considerably influence any separation of the REE-minerals from barren gangue minerals prior to the chemical dissolution and stage-wise chemical extraction of the single REE. This is particularly true to carbonatitic REE-ores as the dominant global source of REEs, and this will be highlighted from a beneficiation point of view in this paper. Further, several aspects of the Ashram Deposit, a promising Canadian REE-project that is held by the Commerce Resources Corp. (CRC), will also be discussed.

Keywords:

Rare earth market – Rare earth mineralogy – Rare earth beneficiation – Flotation – Ashram deposit

Seltene Erden – Aspekte des Marktes und der Aufbereitung

Die sogenannten Seltenen-Erden-Elemente (englisch als REE abgekürzt) sind eine Gruppe von Nebengruppenelementen des Periodensystems der Elemente (PSE), zu denen gewöhnlich die 15 Lanthaniden und Yttrium, mitunter auch Scandium gerechnet werden. Es sind „Hochtechnologiemetalle“ mit großer wirtschaftlicher Bedeutung und dynamisch wachsendem Bedarf, besonders hinsichtlich der Permanentmagnetindustrie. Obwohl oft gemeinsam gruppiert hinsichtlich Markt und Rohstoff, ist jedes einzelne RE-Element einzigartig bis hin zu seinem Endverbrauch und Zielmarkt. Zum Beispiel sind die REEs, die dem Glaspolieren dienen oder in Katalysatoren genutzt werden, nicht die gleichen, die die Magnetindustrie dominieren. Daher ist das Angebot-Nachfrage-Profil jedes einzelnen REE gesondert zu betrachten. Aus heutiger Sicht führt das mittelfristig teils zu einer Überschussvorhersage z.B. für La, Ce und Y, andererseits zu einer

Defiziterwartung z.B. für Pr und Nd. REE-Erze zeichnen sich durch einige mineralogisch bzw. genetisch bedingte Besonderheiten aus, die auf ihre Aufbereitung, d.h. Abtrennung der Begleitminerale vor einem chemischen Aufschluss des Mineralkonzentrates mit nachfolgender Extraktion der einzelnen REE einen wesentlichen Einfluss haben. Dies betrifft insbesondere die sog. karbonatitischen REE-Erze, die in diesem Artikel als heutige Hauptquelle der Seltenen Erden beispielhaft aus Sicht der Aufbereitung zu Mineralkonzentraten behandelt werden. Dabei wird auch auf einige Aspekte des interessanten Kanadischen REE-Projektes Ashram der Firma Commerce Resource Corp. (CRC) näher eingegangen.

Schlüsselwörter:

Seltenerdenmarkt – Seltenerdenmineralogie – Aufbereitung Seltener Erden – Flotation – Ashram-Lagerstätte

Terres rares - Aspects du marché et de l'enrichissement

Tierras raras – Aspectos de mercado y beneficiación

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1 Introduction

The term Rare Earth Elements (REE) embraces a group of metals of similar chemical features that show a combined natural occurrence in minerals, and therefore ore bodies. Owing to this nuance, they are typically recovered jointly in mineral concentrate form, prior to downstream processing.

The REEs may be defined as the 15 lanthanide elements plus yttrium. At times the element scandium has been included; however, unlike yttrium, scandium is not often present in the same REE bearing minerals. Therefore, with respect to the mineral exploration and mining industry, scandium is rarely recognized as an REE.

In terms of geochemical abundance in the earth crust, the REEs appear in the range of 1000 times more frequent than gold [1]. Therefore, it can be concluded that the REEs are neither overly rare nor are they “earths”, a word that meant “oxides” in the language of the 18th and 19th century when REEs were discovered. It required a long period of development work over the following decades to isolate and extract single REEs from their minerals and oxides using laborious step by step processes [2].

2 REE-market and production

In 2010, an international incident between China and Japan caused a temporary global shortage of REEs and a period of heightened anxiety and subsequent price spike. The Chinese market dominance is clearly evidenced from Figure 1. Owing to these dynamics, a bubble like REE-hype in the years 2011/12 occurred and was followed by a sharp and protracted downturn in the market through 2016, with many REE-exploration projects abandoned (Figure 2).

The market has improved markedly through 2017, and continues through 2018, and the culling of REE projects in the space over the last five years has better positioned its survivors for success.

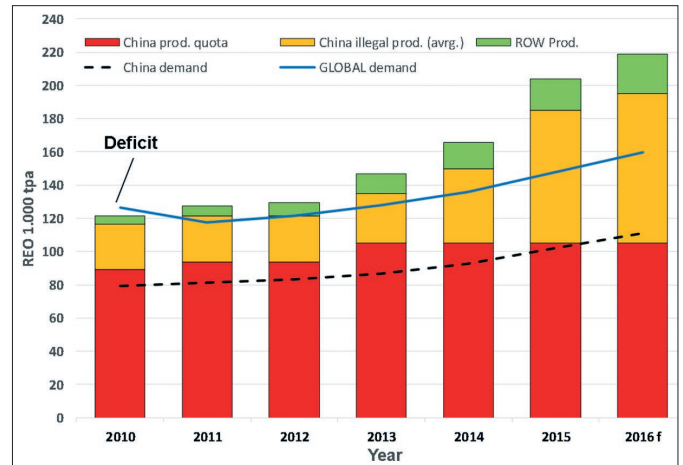


Fig. 1: Global REE supply and demand (replica on [3])

During 2011/12 and several years following, the market was focused on the heavy rare earth elements (HREE, namely Tb, Dy, and Y) and/or the critical rare earth elements (CREE, namely Nd, Eu, Tb, Dy, and Y) with those projects enriched in such REEs assigned a premium in the market over this period.

However, since this time, the market and its perception has shifted. With the recent decline of REE for the phosphor industry (Eu, Tb), coupled with the continued advancements to reduce the Dy-content in magnets, the market has refocused on those REE where demand is considered to have the most sustainable growth, as well as constrained supply, over the near through long-term.

These rare earths include Nd, Pr, and to a lesser extent Tb and Dy, collectively known as the Magnet Feed REEs (MF-REE). This subgroup of REE (specifically Pr and Nd) has anchored the REE space with the strongest fundamentals for sustainable growth over the short and long-term, with supply-demand projected to remain tight. However, several other REEs are projected to remain in surplus. KINGSNORTH [3] called that situation an imbalance (Figure 3).

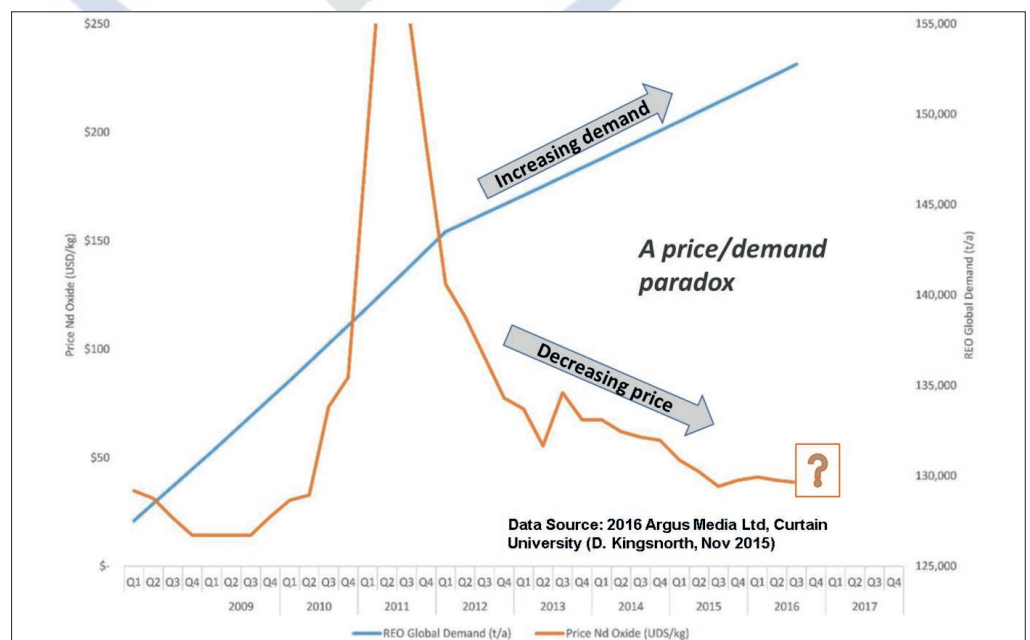


Fig. 2: Price trend of REE (replica on [4])

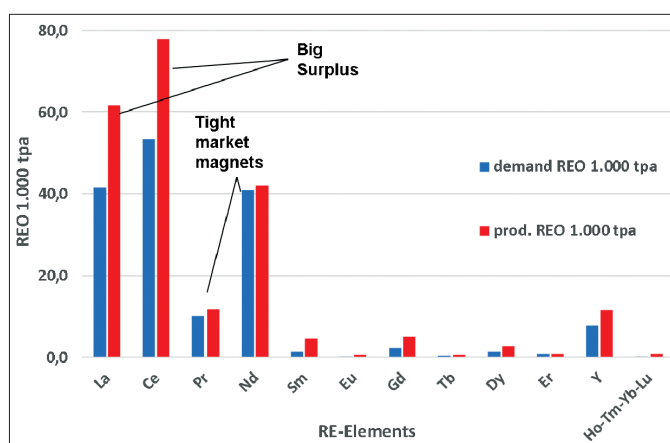


Fig. 3: Global REE imbalance (replica on [3])

No REE deposit globally has an REE distribution that perfectly reflects the market demand for each individual REE. Moreover, there is a wide array of REE distributions among all the REE deposits globally. However, there are some deposits that are far better positioned with an REE distribution that is most aligned with the market with the strongest short term and long fundamentals (i.e. magnets).

A simple take-away from this market dynamic is that each project's success will be largely predicated based on which market(s) its deposit is best aligned with. That being, the deposit's REE distribution, which reflects the relative weighting of each individual REE within the entire REE group. For the foreseeable future, the REE market space with the best short and long-term fundamentals is magnets, and therefore dominated by Nd and Pr. In other words, light rare earth dominated deposits such as carbonatites.

It is clear that China will remain the main source of REE to the global market for the foreseeable future. Although the rest of the world is positioning itself to better capture some of this market share, with the Mount Weld Mine of Lynas Corporation of primary note. Following the USGS numbers, the Chinese proportion of global REE mine production dropped from 97 % in 2011 to 85 % in 2015 [5]. Further, China as main producer of REE, simultaneously remains the main REE-consumer as well [3].

All in all, the market of REEs keeps on ramping up dynamically by 6 to 8 % annual growth on average and 12 to 16 % growth for MF-REE [3].

Production REO 2014 /45/66/	Ard. 160 kt
Separated REO value 2014 (pre-conc., mixes, separated REE)	4 Billion (Mrd) US \$
Supported manufact. Sector (electronic components, Lasers, Batteries, phosphors, Magnets etc.)	2...4.8 Trillion US\$
Supported down-stream economic output north America (Automotive ind., Weapons, Consumer electronics, LED-lightings, Wind turbines etc.)	330 Trillion US\$; (619,000 people employed)

Fig. 4: Table of REE market importance [3,6]

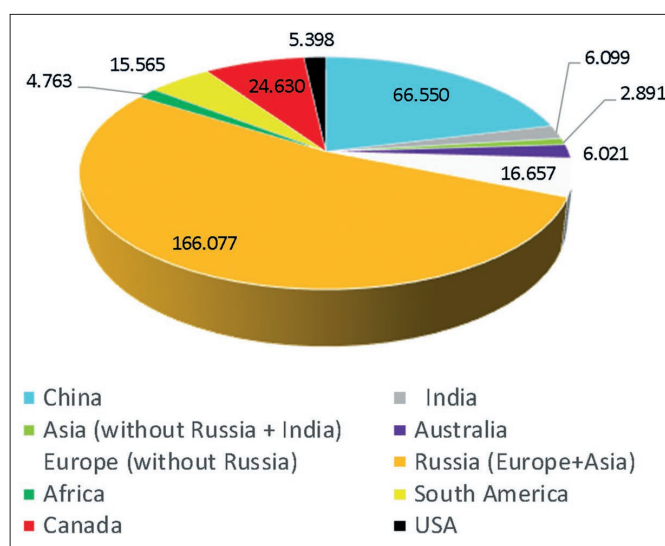


Fig. 5: Global REO Resources 2013, x 1000 t TREO [7]

Even though this market of roughly 160,000 to 200,000 t/a RE-Oxides (REO) is comparatively small compared to many other commodities, its economic importance is large as can be seen from the next table (Figure 4, [3, 6])

The global REO resources are displayed in Figure 5 based on the 2013 numbers of the German "Federal Society of Geo-sciences and Raw Materials" (BGR, [7]).

In contrast, the reserves that are dominated by China, while most of the resources are found in Russia followed by China and Canada.

Calculating roughly on 200,000 t/a REO demand with 315,000,000 t of resources and 29,000,000 t of reserves respectively, a more than 100 years supply guarantee seems to be given.

Facing a steadily increasing REE demand, known strategic importance, and need for stability of supply (see Figure 1), other REE projects are likely to be developed. This may raise the question of which one is the most promising REE

Table 1: Selected aspects of developing REE mining projects (partly from [9-13, 7])

Factor	Remark/example
Tough competition	Chinese mass production, price dumping, illegal production, state subsidies, etc.
Growing but limited market	Threat of temporary imbalance and fall in prices
Regional settings	Infrastructure, power supply, water resources, man power, green popular opposition, etc.
Environmental issues	NORM separation (Th+U), local legacy and disposal acts, site preservation etc.
Heavy developing cost + Capex	20 ... + 50,000 US\$/t REO
Time frame	10 ... 15 years and more, including bankable FS
Mineralogy and genesis	Ore grade, REE-distribution (basket price), gangue and mineralization, weathering, mining concept etc.
Beneficiation issues	Amenability/refractoriness, locking, grain size, gangue, required/doable concentrate grade and by-products, etc

project, that has survived the up and down of prices over the last period of years and is the most likely to succeed.

In 2016, 53 advanced REE projects running on 58 deposits in 16 countries, driven by 50 companies were listed [8].

Geology, mineralogy, processing, local and environmental conditions etc. of any REE project are always unique. Any new REE project may face challenges that are not visible early in the projects development, and hence usually require a tailor-made approach. Table 1 shows some of the influencing factors for new projects.

Of these numerous conditions, some aspects of geological settings, mineralogy and ore beneficiation are to be picked and exemplified as follows.

3 Geological settings and mineralogy

The geological settings of REE seem to be quite special, and there is a multitude of different REE-deposit types that have been described so far.

POHL [14] proposes the following ones:

- carbonatites (post magmatic-hydrothermal bodies),
- metasomatic carbonate hosted ores (Bayan Obo Fe-ore),
- hydrothermal magnetite-apatite ores,
- fluorite-bastnaesite breccia,
- peralkaline/granitoid complexes (Kvanefjeld),
- monazite + apatite bearing residual melts,
- pegmatites,
- skarns,
- lateritic residual over carbonatites (Mt. Weld),
- monazite/xenotime bearing coastal placers,
- residual ionic clay adsorption deposits (weathered granites, S.-China).

The classification of the US Geological Service (USGS) differentiates between 34 deposit types even [15]. How-

ever, it is not the objective of this paper to give another overview or discussion of this in detail.

In summary, one can conclude that carbonatites are the dominant source of REE, followed by ionic clay adsorption type, and to a minor extent by peralkaline rocks and placer deposits. Carbonatites are classified as igneous rocks bearing +50 % primary carbonate minerals, and less than 20 % silica according to the IUGS system [15]. They are expected to host up to more than 80 % of the total world REE resources with light REE (LREE) predominating [4, 15].

About 250 REE-minerals are known, embracing F-carbonates, phosphates, silicates etc., that are described from about 700 occurrences [15, 16]. They can bear up to +60 weight-% of REO.

However, more than 95 % of all REE of the earth crust are estimated to be borne by only three REE-minerals namely monazite, bastnaesite, and xenotime [15].

Aside from the actual REE-minerals, other minerals are able to embed REE in their crystal lattice as substituents of other elements up to more than 10 % REO. Such minerals are zircon, apatite, Nb/Ta/Ti-oxides, fluorite, various silicates etc. A special case are the HREE-enriched secondary deposits on weathered granites of south China where the REE are adsorbed onto clay minerals like kaolinite etc. [17]. Table 2 displays a selection of typical minerals for the recovery of REE with monazite, bastnaesite, xenotime, and as a special case, loparite, being the most important ones on industrial scale.

The diversity and complexity of any REE mineralization makes each deposit unique, often requiring for a tailor-made processing approach. Unlike with other ores of metals such as iron or precious metals, up to more than 15 different valuable mineral commodities can be contained in REE-ores making the processing a challenge. The deposit of Montviel/Canada may exemplify this fact with containing a combination of 19 REE and Nb-minerals of

Table 2:
Selection of important REE minerals, (data from [13, 18-22])

Mineral source	Simplified formula	Assay + REO content	True density	Mohs hardness
Monazite	(Ce,La... Th)PO ₄	50-68 % REO, +LREE	4.9	5.5
Xenotime	YPO ₄	52-62 % Y ₂ O ₃ , +Th, ~5 % U, +HREE	4.6	4.5
Bastnaesite	(Ce,La,...)[CO ₃ /F]	36-56 % Ce ₂ O ₃ , ard. 19 % La ₂ O ₃ , ++LREE	4.5-5.2	4-4.5
Synchisite	Ca (Ce, La, ...) [(CO ₃) ₂ /F]	similar Bastnaesite	3.9-4.15	4.5
Parisite	Ca(Ce, La...) ₂ [CO ₃] ₂ F ₂	53-61 % REO, similar Bastnaesite	4.3	4.5
Loparite	(Na,Ca,Ce,Sr) ₂ Ti,Ta,Nb) ₂ O ₆	42-45 % REO, 8-11 % (Ta,Nb) ₂ O ₅ , + Th (Lovozero)	4.8	6
Fergusonite	(Y,Sr,Ce,U) (Nb,Ta,Ti)O ₄	31-42 % Y ₂ O ₃ , 1-4 % ThO ₂ , 1-6 % UO ₂ , + HREE	5.6-6.2	5.5-6.5
Aeschnynite	(Ce,Ca,Th,Y) (Ti,Nb) ₂ O ₆	20-24 % REO, 11-17 % ThO ₂	4.9-5.1	5-6
Eudyalite	Na ₃ (Ca,Fe,Ce...) ₃ Zr((OH,Cl)/(Si ₃ O ₉) ₂)	up to 2.9 % REO, + HREE	2.8-3	5-5.5
Steenstrupine	Na ₁₄ Ce ₆ (Mn,Fe) ₃ (Th,U)(Si ₆ O ₁₈) ₂ (PO ₄) ₇ ·3H ₂ O.	REE+U/Th, up to 1 % U, (Kvanefjeld)	3.4	5
Lateritic ionic clays	Adsorbed REE-ions on clay minerals	Ce ₂ O ₃ 1-7 %, Nd ₂ O ₃ 5-30 %, Y ₂ O ₃ 10-63 %, + HREE! (South China)	–	–

a great chemical variety comprising silicates, fluor-carbonates, carbonates, phosphates and oxides [15].

Owing to the special characteristics of geology and mineralogy of REE-ores, a careful mineralogical investigation by automated mineralogy, over the course of any beneficiation tests, is a MUST.

4 Mineral processing aspects

Each and every REE exploration or mining project shows distinctive features and conditions (see Table 1). Thereby, the mineralogy of REE-ores dictates the method(s) of mineral processing and critically influences the feasibility of any project. The processing usually comprises the separation of the REE-minerals from the barren gangue prior to the chemical cracking of the mineral concentrate and separation of the single REE. This is true of the carbonatitic REE-ores as the dominant global source in particular. The following aspects of processing are focused on this type of ore.

The flow sheet in Figure 6 summarizes and simplifies a usual process flow scheme for any REE-ore beneficiation. Out of the four main stages of this scheme presented, the mineral processing step is to be discussed here on select aspects given by mineralogy.

There are several good papers available that deal with special beneficiation flow sheets for different REE-ores. However, it is not the objective of this paper to give another overview of this in detail. The references [19, 23-26] may be taken for an overview about that issue.

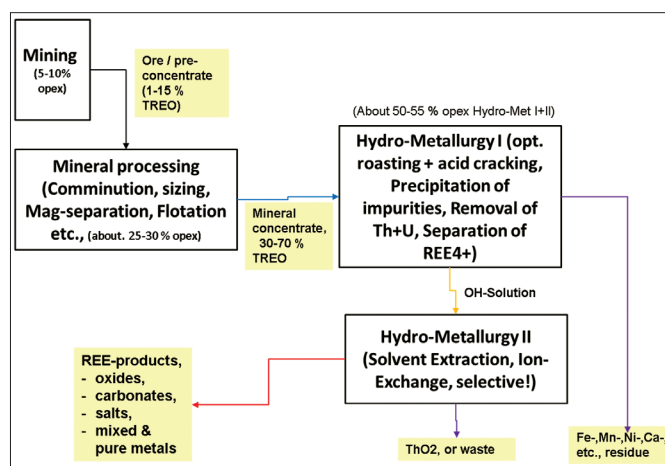


Fig. 6: General flow scheme of REE-ore beneficiation ([7, 27], amended)

The main upgrading process for the beneficiation of carbonatitic ores is flotation that can be partly combined with magnetic and gravity separation stages on a case by case basis.

There is a multitude of flotation collectors and other reagents that have been recommended, and successfully applied to the flotation of REE-minerals. A couple of reagent application aspects are presented in Table 3.

Of particular note, in terms of a full-scale collector application are various hydroxamates, fatty acid formulations, and phosphoric acid esters. The choice of reagents depends strongly on the mineralogy of the ore and usually is initially completed on the basis of individual experience of the responsible staff.

Reagent type	Application remarks
Hydroxamate type collectors (HXA)	<ul style="list-style-type: none"> • selektive for REE, +tarnished sulfides, Fe +Ti + Nb + Sn-minerals etc. • aliphatic and aromatic ones, (30-60 % act. subst. 1/55/) • good Chinese brands (Florrea)! • T-rise may improve recovery
Fatty acids, FA-type collectors (carboxylates)	<ul style="list-style-type: none"> • strong and rather non-selective • improved performance on elevated T, • need of considerable depressant dosage (Mountain Pass etc.) • mix with HXA may be useful
Other select collectors	<ul style="list-style-type: none"> • oleyl sarcosine • alkyl sulfo succinamate, (Y-minerals) • alkyl sulfonate, alkyl phosphate etc. (for inverse flotation)
Collector combinations	usually better recovery, sequence of dosage to be checked
pH regulators (soda ash!, NaOH, HCl, H ₂ SO ₄ etc.),	<ul style="list-style-type: none"> • carbonate gangue buffers pH drop • may show activating or depressing action tool
Depressants	<ul style="list-style-type: none"> • great variety available, • may influence pH too, (org. acids!, fluorides) • dosage to be carefully tested • ligno sulfonates for carbonates and sulfates (biopolymers Pionera ...) • water glass, CMC, starch etc. f. silicates + Fe-minerals etc.
Frother	<ul style="list-style-type: none"> • wide range available (PGE, MIBC, alcohols, pine oil etc.) • sometimes sufficient frothing by collector formulation • use depending on PSD, slime proportion etc.
Dispersants	<ul style="list-style-type: none"> • slime ruling! • trade-off versus de-sliming (REE-loss with slimes), • may act as depressant too (Na-silicate, ligno sulfonates, ...)
Activators	<ul style="list-style-type: none"> • soda ash (OH-bridging) • ion catcher, Na-silicofluoride etc. • Pb-salts?

Tab. 3:

State of flotation reagents for REE-minerals, (partly from [19, 23-26, 28])

In terms of magnetic separation, the type of matrix used for wet high intensity magnetic separation (WHIMS) is of crucial importance and requires careful test work. Provided that a suited matrix can be found, a successful magnetic separation can be accomplished for even a particle size below 25 microns. The presence of para- or even ferrimagnetic gangue may require a multi-stage approach.

Worth mentioning is the application of advanced pre-sorting systems after pre-crushing that may help cutting short the capacity and capex of the downstream upgrading facilities for milling and flotation etc.

From the experience of the authors, X-ray sensing systems like the ones of the German company “Tomra Sorting” particularly when using the XRT-technology may deliver good results with less than 5 % REE-loss in the rejected coarse tails. However, this technology is limited to a fraction size between 10 and 50 mm about, and not suitable to all REE-ores.

From the view of ore mineralogy and genesis, a bunch of general influencing factors for the mineral processing are collected and displayed in Table 4.

Some of the mineralogical beneficiation aspects from Table 4 can be further exemplified by the next tables and pictures.

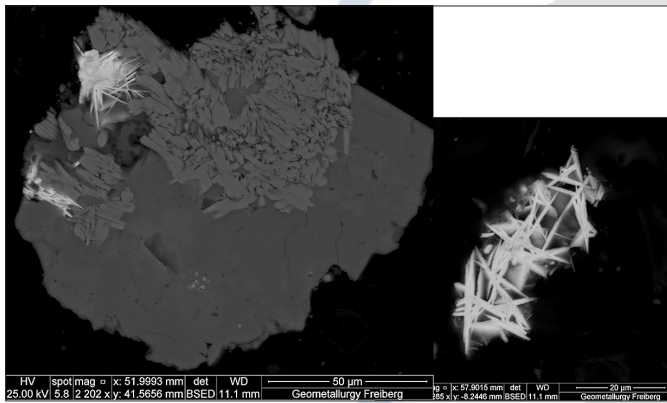


Fig. 7: Acicular and brittle structures of REE fluor carbonates (MMP data)

Table 4:
Selected natural factors for processing carbonatitic REE-ores

Factor by mineralogy	Explanation
Paragenesis (Association)	Chemically similar gangue minerals, same cat- and anions (Ca, F, CO ₃), ... tricky separation by flotation, NORM (Th+U)!
Weathering	Slime formation trend can occur, even enrichment of REE in the slime fractions, looming loss with de-sliming steps
Grain size/locking	Often finely inter-grown, partly multi-stage milling down ~20 µm needed (ISA application?)
Milling properties/hardness	Remarkable REE-enrichment in the fines can occur (slime problem, de-sliming loss)
Geochemical spread of REE	Bound by various REE-minerals with zoning and variation of REE-content that may appear; + even partly dissemination into the lattice or on the surface of gangue minerals possible; (may cause limited recovery!)
Magnetic properties	Fluctuating, partly para-magnetic properties of REE-min., gangue partly too or even ferrimagnetic
Density of REE-minerals	Usually pretty high, but often too fine GSD for gravity separation or associated with high density gangue (baryte etc.)
Floatability/surface properties of REE-minerals	Often similar to associated minerals, causes usually more or less complicated multi-stage techniques (bunch of collectors and depressants, pH-control, special conditioning, water-exchange, hot processing, a. o. gadgets)
Potential by-products	Fluorite, baryte, Fe-Nb-Ta-Zr-minerals, U/Th, etc. (economy vs. complexity)

Table 5: PSD and mineral distribution of the Dong Pao rich ore cap, [30]

Size fraction [µm]	Distribution [%]				Assaying [%]		
	mass	REO	baryte	fluorite	REO	baryte	fluorite
-15	16.8	43.9	7.5	4.1	35.7	22.3	3.9
15-32	7.4	8.0	7.3	5.1	14.7	48.8	11.2
32-63	5.7	5.4	5.3	4.3	12.5	48.6	12.7
63-100	9.1	9.7	10.2	7.3	13.9	58.3	13.4
100-315	11.1	10.9	11.4	10.9	12.9	53.4	16.5
315-500	6.5	6	6.5	8.4	12.1	51.7	21.6
500-1000	12.2	7.7	12.2	17.4	8.3	51.9	23.9
1000-2000	12.4	4.8	14.8	18.0	5.1	62.0	24.4
+2000	18.8	3.6	24.8	24.5	2.6	68.1	21.8
total	100	100	100	100	13.1	51.9	16.8

Figure 7 displays acicular and brittle structures of REE-minerals that caused great slime proportions and hence heavy REE-losses in the de-sliming stage after grinding and prior to flotation.

In Figure 8, a liberated zircon crystal is shown that featured zoning and infiltration by iron and REE causing detrimental flotation properties when trying a separation of zircon from xenotime by HXA.

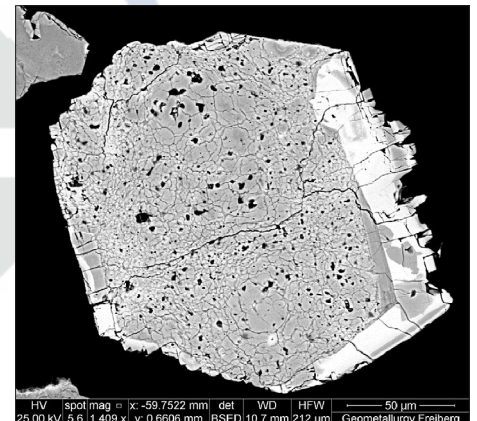


Fig. 8:
Zoning of zircon, REE+Fe infiltration [31]

A mineral and REO distribution of the Dong Pao deposit in North Vietnam can be seen in Table 5 that was caused by heavy weathering creating a rich ore cap that seemingly was dug away and sold privately by the local people during the REE hype [29].

With this rich ore, the slime formation trend of REE-minerals could be used to enrich bastnaesite and produce + 30 % REO concentrates from the fine fractions simply by washing and hydro cyclone sizing [30].

5 Example Ashram

Out of the multitude of projects from the last REE-hype, many REE-exploration projects have been abandoned with only a select few still being advanced. One of the survivors of this culling process is the “Ashram” Project of the company Commerce Resource Corporation in Canada, that will be introduced in the following section in terms of mineralogy, beneficiation concept, and project development. Figure 9 gives an overview of the Ashram Deposit.

Being characterized by a comparatively simple mineralogy (REE and gangue), good grade, high-tonnage, top jurisdictional location, and a well-balanced REE distribution enriched in the MF-REEs, the carbonatite hosted Ashram Deposit in Canada is a promising potential source of rare earth minerals such as monazite, and to a lesser extent bastnaesite, and xenotime.

Figure 10 displays an MLA-shot of the Ashram Deposit material after rod milling. The grouped modal mineralogy reveals a combination of the aforementioned REE-minerals with carbonates, fluorite, minor apatite, sulfides, and few silicates (Table 6, [32])

A simplified consideration like this is suitable solely for all these REE-minerals and acts likewise during the beneficiation process caused by similar flotation and magnetic properties, and therefore may be handled as one group.



Fig. 9: Map of Quebec and situation of the Ashram Deposit [32]

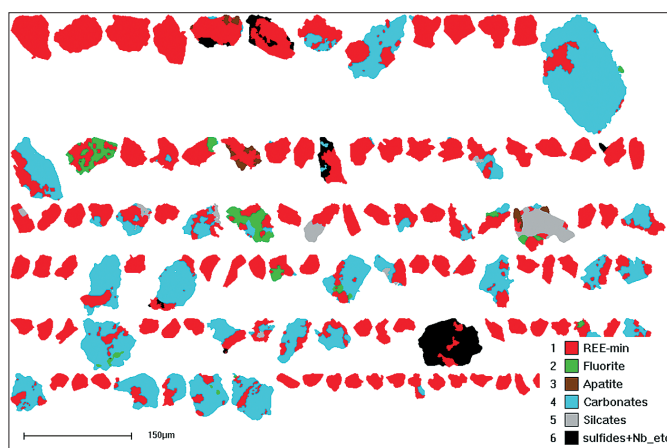


Fig. 10: REE-mineral locking, Ashram material after rod milling [32]

An essential aspect of this work was the development of separation methods by flotation and wet high magnetic separation (WHIMS) to separate the REE-minerals from fluorite and carbonate gangue.

In 2011, Commerce Resource Corporation, based in Vancouver/Canada and sole registered title holder of the Ashram Deposit, engaged MMP aside from other partners to support the development of a beneficiation technique for producing a rare earth mineral concentrate in excess of 30 % TREO with a total REO recovery of more than 65 % from Ashram Deposit material.

The separation of REE-minerals of the phosphate and fluoro-carbonate type, from gangue minerals such as apatite, iron bearing carbonates, and fluorite by flotation was a challenging task owing to quite similar flotation properties.

Over the course of the test programs, Commerce Resource Corp. was able to successfully develop various beneficiation processes to produce high grade REE mineral concentrates of +40 % REO and at modest recovery that are amenable to proven cracking and REE-separation techniques without any detailed optimization of all processes being undertaken.

Tab. 6:
Modal mineralogy
of the Ashram material
sample III
(grouped, [32])

Mineral	Wt.-%
REE – Monazite	2.94
REE – FC + others	1.00
Apatite	1.15
Fluorite	6.70
Calcite	0.26
Dolomite	44.42
Ankerite	32.47
Siderite	7.77
Quartz	1.35
Feldspars	0.04
Phyllosilicates	0.78
Sulfates	0.00
Cu-Fe-Sulfides	0.57
Fe-Ti-Ca-Phase	0.25
Nr-Zr-Yb-Phase	0.13
Total	100.00

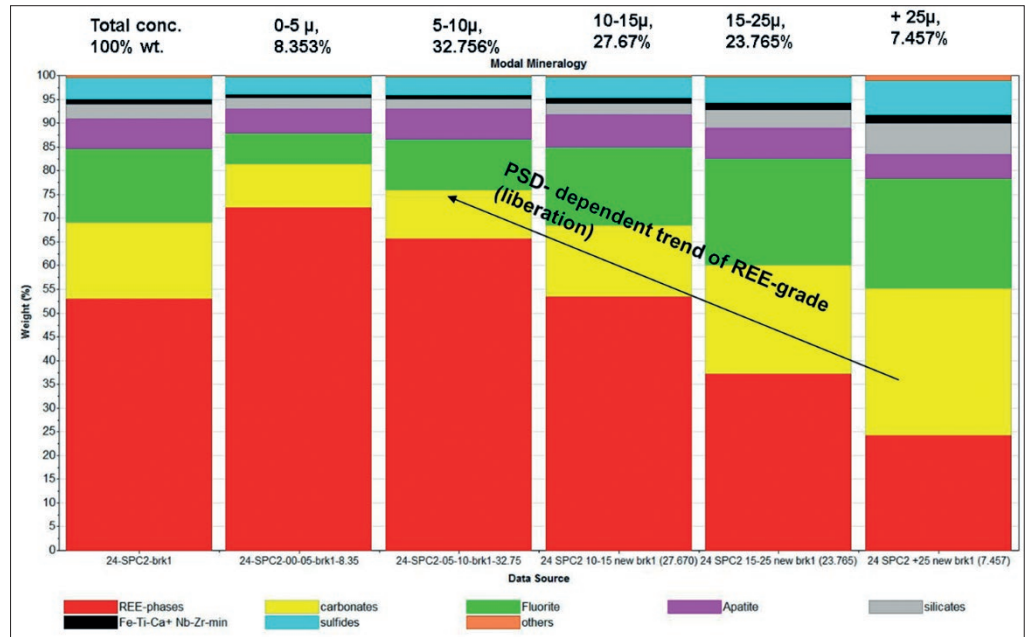


Fig. 11:
Modale mineralogy of a cleaner
flotation concentrate (32 %, [32])

Two alternative basic beneficiation techniques were developed:

- a mere multistage rougher and cleaner REE-flotation procedure
- and a combined technique with rougher bulk flotation and WHIMS.

Open cycle flotation tests that successfully applied known flotation reagents and a special pH-shift showed a recovery

of about 80 % in the rougher plus scavenger stages, with REE-mineral grades of up to 45 % TREO in the final cleaner stages [32].

As Figure 11 may explain for a 32 %-REO concentrate, the mineral grade depends on the particle size, and hence, most likely on the liberation. For the fine fraction below 10 μm , REE-mineral grades of +65 % were reached. However, for the +25 μm fraction, the grade dropped down to minus 25 % while the carbonate and fluorite content increased.

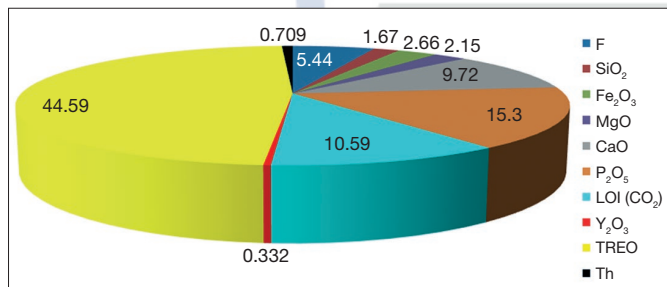


Fig. 12: Assaying of a high-grade REE-flotation cleaner concentrate [32]

Figure 12 displays the mineral composition of a high grade REE-mineral flotation concentrate of 45 % REO. As a main reason of associated carbonate remainders, lockings were indicated by automated mineralogy. This level of grade is expected to can be further enhanced by improved grinding and sizing techniques.

Although development of a mere REE-flotation approach was put on hold in favor of a combined process of REE+fluorite-flotation, carbonate leach, and WHIMS (Figure 13), the results indicate a promising method for

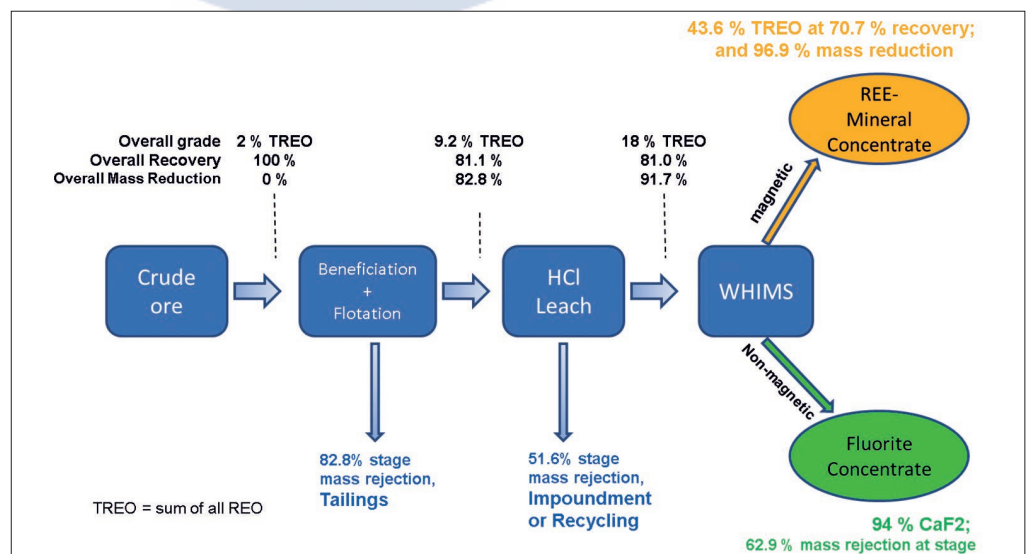


Fig. 13:
Preferred beneficiation flow sheet
for the Ashram material [33]

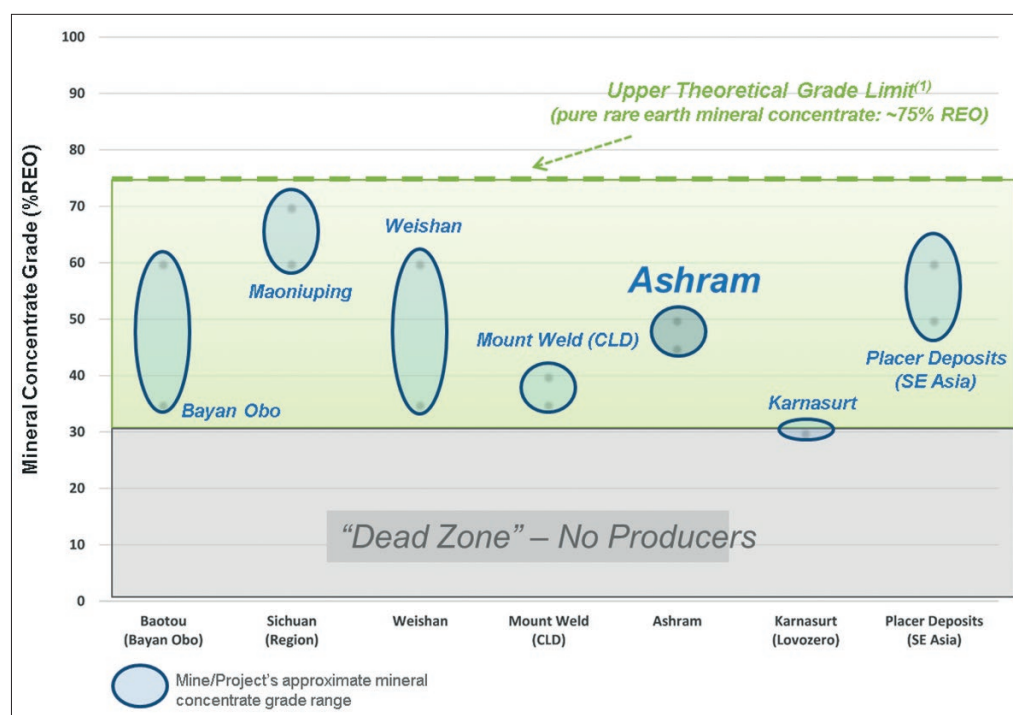


Fig. 14:
Flotation concentrate grades of
different REE ore deposits [4]

beneficiating REE-carbonatite ores with fluorite bearing gangue by only flotation.

The combined process, which offers an interesting extra bonus of producing saleable fluorite products, was developed onto a level of pilot scale.

The incomplete state of work about both techniques developed holds good potential for a remarkable improvement of the process performance by further investigations downstream of the project.

As such, the test work results brought the Ashram Project onto a performance level of known and successfully operating REE mines, as is exemplified by the Figure 14 outlining a comparison of concentrate grades with global producers [32].

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