Overview of REE Deposits and Mines in the World and in Brazil

Anthony N. Mariano, Consultant, Carlisle, MA
Anthony Mariano, Jr., Consultant, Carlisle, MA
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REE Exploration Experience Spans 45 years
## Major Rare Earth Sources

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<thead>
<tr>
<th>Mineral</th>
<th>Composition</th>
<th>Occurrence</th>
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<tbody>
<tr>
<td>Bastnäsite (Ce)</td>
<td>$\text{REE(CO}_3\text{)}\text{F}$</td>
<td>Carbonatites</td>
</tr>
<tr>
<td>Monazite (Ce)</td>
<td>$(\text{REE})\text{PO}_4$</td>
<td>Beach Sands, Hydrothermal</td>
</tr>
<tr>
<td>Xenotime (Y)</td>
<td>$(\text{Y,REE})\text{PO}_4$</td>
<td>Beach Sands, Hydrothermal</td>
</tr>
<tr>
<td>Loparite (Ce)</td>
<td>$(\text{REE,Na,Ca})(\text{Ti,Nb,Ta})\text{O}_3$</td>
<td>Alkaline Igneous Massif</td>
</tr>
<tr>
<td>South China Clays</td>
<td>Ion-adsorbed REE+Y</td>
<td>Clays</td>
</tr>
<tr>
<td>Uraninite</td>
<td>REE+Y released as dissolved elements in rafinates from uraninite</td>
<td></td>
</tr>
</tbody>
</table>
Ion-Adsorbed Clays
Xunwu Longnan District, Jiangxi Province, China
Ion-Adsorbed Clays
Mining Procedure

Occurrence

• Ore is a whitish colored regolith soil that is mined from hillsides.
• Surface areas have been exposed by removal of trees and vegetation.
• The ore extraction may be selective along bands that are lighter than adjacent soil.
• This could be fracture dependent where lateritic weathering has been more advanced.
Ion-Adsorbed Clays
Mining Procedure

Processing

• Pits are dug nearby and plastic linings are placed in the pit bottoms to prevent the escape of fluids.
• The pits are filled with a water and ore mixture.
• The pit material is then exposed to leaching with $\text{H}_2\text{SO}_4$ or ammonium sulfate $(\text{NH}_4)_2\text{SO}_4$ to put the REE into solution.
• The fluids are later siphoned downhill into another concrete pool and exposed to oxalic acid.
• REE oxalates $\text{REE(COOH)}_2$ are then precipitated.
• The precipitate is collected in a calcining kiln and fired to 800°C to drive off the $\text{CO}_2$ and $\text{H}_2\text{O}$, producing $\text{REE}_2\text{O}_3$.
• The end product is stored in bags.
Ion-Adsorbed Clays

Although ion-adsorbed REE in clays from South China provide the bulk of HREE to the market place, in other countries, high costs for labor and necessary supplies, power costs, and environmental restrictions may render similar deposits uneconomical.
Supergene REE Mineralization

• A major source of REE and Y occurs in weathered carbonatite laterites.
• Weathering that may exceed 300 meters causes the chemical breakdown of primary minerals (calcite, dolomite, apatite) and the release of REE and Y.
• REE and Y subsequently recrystallize forming high-grade secondary mineralization.
• The supergene products include monazite, gorcexite, goyazite, florencite, churchite, and xenotime as vast accumulations inextricably associated with iron oxides and other residual accumulations.
Supergene REE Occurrences Include...

- Mt. Weld, Australia
- Araxá, Minas Gerais, Brazil
- Catalão, Goiás, Brazil
- Mrima, Kenya
- Mabounié, Gabon
- And other more remote occurrences in the South American Amazon and in Siberia.

- Despite their high-grade and large tonnage, none of these occurrences have yet been exploited.
- There is no conclusive evidence that the REE and Y can be extracted from the supergene minerals on an economic level that can compete with the current world market sources.
Mount Weld, Australia
With no Topographic Expression

March 10, 1980

<table>
<thead>
<tr>
<th>Category</th>
<th>Tonnes (Mt)</th>
<th>Grade (% REO)</th>
<th>Tonnes REO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>1.2</td>
<td>15.6</td>
<td>186,000</td>
</tr>
<tr>
<td>Indicated</td>
<td>5.0</td>
<td>11.7</td>
<td>583,000</td>
</tr>
<tr>
<td>Inferred</td>
<td>1.5</td>
<td>9.8</td>
<td>148,000</td>
</tr>
<tr>
<td>Total</td>
<td>7.7</td>
<td>11.9</td>
<td>917,000</td>
</tr>
</tbody>
</table>

- Initial mining completed by Lynas Corporation in June 2008
- 773,000 metric tons of ore mined at an average grade of 15.4% REO
- Monazite, REE-bearing crandallite-group, cerianite, rhabdophane, churchite
- Mt Weld Resource Estimate – Central Lanthanide Deposit
Supergene Minerals – MT. Weld, Australia

Monazite pseudomorph after apatite

Monazite pseudomorph after rhabdophane

Florencite pseudomorph after pyrochlore

Churchite $\text{YPO}_4 \cdot 2\text{H}_2\text{O}$
Pseudomorphs of Supergene Monazite After Apatite

Mt. Weld, Australia

Araxá Brazil
Supergene Monazite
light greenish yellow in ferric iron-rich
laterite
Araxá, Brazil
(34-A-3)
(coll. A.N.M. January, 1968)

Supergene Monazite
replacing massive apatite mineralization
Araxá, Brazil Furo O-IXMO, 191.25
meters
(12-A-1)
Pseudomorphs of Monazite after Apatite prisms in Carbonatite – Araxá, MG, Brazil

These pseudomorphs are the result of descending water that is enriched in REE from the dissolved primary minerals in the upper level weathered carbonatite. This section of drill core illustrates the leaching of Ca from the apatite and its replacement by REE as a result of the high affinity (partition coefficient) of REE for phosphate.
Supergene Monazite
Araxá Carbonatite
Minas Gerais, Brazil

Normal Light

Un-Filtered
Shortwave UV
Pseudomorph of Supergene Monazite After Apatite (T-537F) Araxá, Brazil

(Horizontal distance 0.7 mm)
Araxá Apatite Concentrates Chondrite-Normalized Plot

- T-793O Carbonatite $\sum$REE+Y = 0.7034 wt.%
- T-793N Silico-carbonatite $\sum$REE+Y = 0.8611 wt.%
Un-Filtered Shortwave UV – Pyrochlore Ore – Araxá, Brazil

Selective reflection of the green wavelength in the visible spectrum confirms the presence of substitutional LREE in pyrochlore. The $\Sigma$ REE in this pyrochlore is $\approx 7$ wt. %. The black opaque mineral is magnetite.
## Apatite with Substitutional REE

<table>
<thead>
<tr>
<th>Location</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oka, Quebec</td>
<td>Carbonatite</td>
</tr>
<tr>
<td>Nolan’s Bore, Australia</td>
<td>Carbonatite</td>
</tr>
<tr>
<td>Mushgai Khudag, Mongolia</td>
<td>Carbonatite</td>
</tr>
<tr>
<td>Phalaborwa, South Africa</td>
<td>Carbonatite</td>
</tr>
<tr>
<td>Kola Peninsula</td>
<td>Carbonatite and Alkaline Massifs</td>
</tr>
<tr>
<td>Hoidas Lake, Saskatchewan</td>
<td>Hydrothermal in Granites</td>
</tr>
<tr>
<td>Mineville, New York*</td>
<td>Tailings from Magnetite Mining</td>
</tr>
</tbody>
</table>

*Mineville may be the only Y and HREE dominant source currently known
Ancylite (Ce) 
$\text{SrREE(CO}_3\text{)}_2(\text{OH})\cdot\text{H}_2\text{O}$

LREE-Dominant $\approx 50 \text{ wt. } \% \text{ REO}$

An exploration target in the Bear Lodge Carbonatite Complex of northeastern Wyoming
Allanite (Ce)  \((\text{Ce,Ca,Y})_2(\text{Al,Fe}^{2+},\text{Fe}^{3+})_3(\text{SiO}_4)_3(\text{OH})\)

Allanite – Hydrothermal, Mountain Pass, CA

Allanite – Pegmatite, Timmins, Ontario

- Allanite is found in abundant quantities in many different geologic environments
- In almost all cases it is LREE dominant
- Low quantities of \(\Sigma\text{REE+Y}\) relative to bastnäsite and its refractory nature diminish its value as an economic source for REE and Y.
Bastnäsite (REE)CO$_3$F

Major World Source of LREE
- Bayan Obo, Inner Mongolia, China
- Mianning, Sichuan, China
- Weishan, Shandong, China
- Mountain Pass, California, USA
- Karonge, Burundi

Potential Sources
- Dong Pao, North Vietnam
- Wigu Hill, Tanzania
- Kizilcaören, Turkey
- Wicheeda Lake, British Columbia, Canada
- Bear Lodge, Wyoming, USA
Sichuan REE Carbonatites

Fig. 1 Map Showing Locations of the Sichuan REE Carbonatite Districts.
Bastnäsite, Mountain Pass, CA

Normal Light

Unfiltered Shortwave UV

mm scale
Bastnäsite Carbonatite
Mianning, Sichuan, China
XPL Micrograph

Bastnäsite Carbonatite
Mianning, Sichuan, China
CL Micrograph

Brown – Bastnäsite
Orange – Calcite
Blue - Fluorite

HD ≈ 4 mm
Bastnäsite in Carbonatite, Mountain Pass, CA

XPL Micrographs

HD = 1.76 mm

HD = 4.4 mm
Parisite - $\text{Ca(REE)}_2(\text{CO}_3)_3\text{F}_2$  Mountain Pass, CA
Monazite, Mountain Pass, California, USA

HD = 4.4 mm
Bastnäsite, Allanite and Ancylite

Bastnäsite \[(\text{REE})(\text{CO}_3)\text{F}\]
Allanite \[(\text{REE},\text{Y},\text{Ca})_2(\text{Al,Fe}^{2+},\text{Fe}^{3+})_3(\text{SiO}_4)_3\text{OH}\]
Ancylite \[\text{Sr}(\text{REE})(\text{CO}_3)_2(\text{OH})\cdot\text{H}_2\text{O}\]

- These minerals are virtually always LREE dominant, even when found to be co-crystallized with other HREE dominant minerals.
- In rare cases they have been reported as HREE dominant in which case they occur only in trivial quantities.
Monazite (REE)PO₄ 70% REO

Geologic Environments
- Beach Sands
- River Placers
- Metamorphic Rocks
- Carbonatites

- May be byproduct of Ti and Sn mining
- May be very high in Th
- May have major Nd

Potential Sources in Carbonatites
- Kangankunde, Malawi
- Wicheeda Lake, B.C., Canada
- Bear Lodge, Wyoming, USA
Monazite (Nd)  Lemhi Pass, Idaho, USA

• This rock sample was collected on August 9, 1976 by Tony Mariano and Ted Paster while working for Molycorp.
• The grey groundmass in the BSE micrograph is specular hematite. The green grains in the XEM micrograph are thorite. All of the orange grains are monazite (Nd).
Monazite in Carbonatite, Kangunkunde, Malawai

PPL
HD = 1.76 mm

XPL
HD = 1.76 mm

Monazite (Nd) – Lemhi Pass, ID
Xenotime, one of the best sources for Y and HREE is found in small quantities, most often with larger quantities of monazite, in granitic, pegmatitic, gneissic rocks and in stream and beach placers. Un-sustained concentrates are periodically produced in cassiterite and ilmenite mining of beach sands from Thailand, Indonesia, Malaysia, and Australia.

Hydrothermal vein mineralization of xenotime in quartzites occurs in the John Galt deposit of Western Australia and in the Wheeler River “Maw Zone” of the Athabaska Basin, Saskatchewan.

Xenotime is also reported together with synchysite (Y) in peralkaline syenites and nepheline syenites of AK-Tuz: Kyzyl-Ompul, Kyrgyzstan.
Xenotime
Pitinga

Tetragonal Grains
Concentrate from 1995

Tetragonal Grains from Tailings
Collected July, 2007
Xenotime, Pitinga

Cathodoluminescence and X-ray Element Map Micrographs of Pitinga Madiera Granite showing xenotime, thorite, cryolite, zircon, and feldspars.

CL Micrographs horizontal distance = 4mm
Euhedral Xenotime, Tetragonal Dipyramids

Martiniano Area, Serra Verde, Goiás, Brazil
Xenotime and Monazite in Paragneiss

Highland Falls, New York
Xenotime in a Heavy Mineral Concentrate
Defocused-Beam Cathodoluminescence Showing Yellow-Green CL

(Horizontal distance 46 mm)
Xenotime in Sandstone, Beatty River, Canada

Defocused-beam cathodoluminescence showing major interstitial xenotime

Interstitial Xenotime
Yellow CL from Dy$^{3+}$ activation
Red CL, quartz

Courtesy of Great Western Minerals Group LTD
Zircon is often the heavy mineral in beach sands and river placers. It is a byproduct of Sn, Ti, and Au mining.

Currently, Zircon from some occurrences is being considered as the major source of HREE. The $\Sigma$REE+Y in zircons rarely exceeds 1 wt. %.

The strong refractory nature of zircon and its resistance to chemical dissolution negate its consideration as a competitive HREE source.

Zircon concentrates are transportation sensitive. Accessibility close to ocean and river transportation would be a preferred source.
In the Pitinga granites, zircon constitutes the most abundant accessory mineral, most often representing 75 % by wt of the heavy mineral concentrates.
Pitinga zircons are predominantly light cocoa-brown in color, but include lesser amounts of cream-colored grains.
The morphology invariably consists of euhedral crystals as dominant tetragonal dipyramids with only a slight modification by the first order prism.
The grain size range of Pitinga zircons is from slightly <0.1 mm, to >1.5 mm, but the average grain size is estimated to be 0.5 mm.
Chondrite-Normalized Plot - Pitinga Zircons

(T-713W) Zircon Concentrate from Sample collected in UBM Basin 5 on August 5, 2006 \( \Sigma \text{REE+Y} = 0.7130 \% \)

(T-713E) Zircon Concentrate from "Columbite Concentrate" collected December 12, 1995 \( \Sigma \text{REE+Y} = 0.9022 \% \)

<table>
<thead>
<tr>
<th>Element</th>
<th>T-713W (%)</th>
<th>T-713E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>La</td>
<td>0.0048</td>
<td>0.0184</td>
</tr>
<tr>
<td>Ce</td>
<td>0.0464</td>
<td>0.0358</td>
</tr>
<tr>
<td>Pr</td>
<td>0.0057</td>
<td>0.0036</td>
</tr>
<tr>
<td>Nd</td>
<td>0.0280</td>
<td>0.0171</td>
</tr>
<tr>
<td>Sm</td>
<td>0.0103</td>
<td>0.0059</td>
</tr>
<tr>
<td>Eu</td>
<td>0.0003</td>
<td>0.0004</td>
</tr>
<tr>
<td>Gd</td>
<td>0.0120</td>
<td>0.0070</td>
</tr>
<tr>
<td>Tb</td>
<td>0.0065</td>
<td>0.0042</td>
</tr>
<tr>
<td>Dy</td>
<td>0.0682</td>
<td>0.0470</td>
</tr>
<tr>
<td>Ho</td>
<td>0.0199</td>
<td>0.0144</td>
</tr>
<tr>
<td>Er</td>
<td>0.1020</td>
<td>0.0754</td>
</tr>
<tr>
<td>Tm</td>
<td>0.0266</td>
<td>0.0213</td>
</tr>
<tr>
<td>Yb</td>
<td>0.2140</td>
<td>0.1750</td>
</tr>
<tr>
<td>Lu</td>
<td>0.0330</td>
<td>0.0273</td>
</tr>
<tr>
<td>Y</td>
<td>0.3240</td>
<td>0.2602</td>
</tr>
</tbody>
</table>
Despite the occurrence of fergusonite in many geologic environments and its attractive chemistry, it has never been found to occur in quantities sufficient for economic exploitation on a sustained level.
Fergusonite

São Jose Area, Serra Verde, Goiás, Brazil
Idioblastic Fergusonite Prisms with Zircon and Allanite in Quartz-Biotite Gneiss
Matamec Surprise Area – Kipawa Quebec
Loparite (REE,Na,Ca)(Ti,Nb,Ta)O₃

Interpenetrating Octahedra as Multiple Twinning in Dominant Cubes from Lovozero, Kola Peninsula, Russia

In nepheline syenite massifs, the ore contains 2%-3% Loparite (Ce). REO ≈ 30-36 wt. %; Nb₂O₅ ≈ 10 wt. %; Ta₂O₅ ≈ 0.69 wt. %.
Eudialyte

\[ \text{Na}_{15}\text{Ca}_6(\text{Fe}^{2+},\text{Mn}^{2+})_3\text{Zr}_3(\text{Si}_{25},\text{O}_{73})(\text{O,OH,H}_2\text{O})_3(\text{Cl,OH})_2 \]

- Eudialyte may also contain Y and HREE in amounts exceeding 4 wt.%. The mineral is easily dissolved in weak acids.
- Recent research in chemical processing of eudialyte from Kipawa, Quebec has shown positive results in the isolation of REE and Y oxides, and including ZrO₂ exclusive of SiO₂.
Eudialyte and Mosandrite in Peralkaline Syenite

Kipawa, Quebec
Chondrite-Normalized Plots - Kipawa Eudialytes and Britholite, Bayan Obo Bastnäesite

- Kipawa K-2 (Eudialyte)
- Kipawa K-3 (Eudialyte)
- Kipawa K-1 (Britholite)
- Bayan Obo Bastnäesite
Eudialyte Physical Concentrate, Norra Kärr, Sweden

<120, >200 mesh (mm scale)
Mosandrite Concentrate \((\text{Na}, \text{Ca}, \text{REE})_3 \text{Ti}(\text{Si}_2\text{O}_7)_2\text{OF}_3\)  
Kipawa Quebec
Chondrite-Normalized Plots- Eudialytes, Britholite, Mosandrite
Mosandrite and Eudialyte
Kipawa, Quebec
Britholite  \((\text{REE}, \text{Y}, \text{Ca})_5(\text{SiO}_4, \text{PO}_4)_3(\text{OH}, \text{F})\)

This mineral has the potential for occurring in ore quantities in skarns associated with syenite gneiss in Kipawa, Quebec.

Massive Britholite (Ce) - Oka, Quebec

Britholite (Ce) Concentrate from Skarn - Kipawa, Quebec
Cathodoluminescence Micrograph of Peralkaline Granite
Pajarito Mountain, New Mexico, USA
Green – Kainosite
Red – Albite
Orange – Gittensite
Pink needle – Apatite
## REE in Uraninites (UO₂)*

<table>
<thead>
<tr>
<th>Location</th>
<th>Geologic Environment</th>
<th>∑REE</th>
<th>LREE/HREE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rössing Mine Namibia</td>
<td>Alaskitic-Granite</td>
<td>2.52%</td>
<td>0.41</td>
</tr>
<tr>
<td>Faraday Mine Ontario, Canada</td>
<td>Granite Pegmatite</td>
<td>2.89%</td>
<td>1.10</td>
</tr>
<tr>
<td>Fission Mine Ontario, Canada</td>
<td>Metasomatic Vein Dike</td>
<td>1.89%</td>
<td>1.03</td>
</tr>
<tr>
<td>Eldorado Mine N.W.T., Canada</td>
<td>Hydrothermal Vein Deposit</td>
<td>0.71%</td>
<td>1.15</td>
</tr>
<tr>
<td>Collons Bay Saskatchewan, Canada</td>
<td>Unconformity Type Deposit</td>
<td>0.13%</td>
<td>0.08</td>
</tr>
<tr>
<td>Pine Creek Geosyncline Australia</td>
<td>Unconformity Type Deposit</td>
<td>0.17%</td>
<td>0.19</td>
</tr>
</tbody>
</table>


*These analyses do not include Y*
Colluvial REE Deposits

One of the interesting sources for independent REE and Y mineralization can be in large volume colluvial deposits derived from weathered granite or metamorphic rocks. In some occurrences heavy mineral accumulations can represent several percent of the colluvium.

Heavy minerals may include liberated coarse-grained xenotime and monazite that are readily amenable to well established physical processing techniques without resorting to grinding.

An example of this scenario under current exploration by Mining Ventures of Brazil is the Serra Verde occurrence of Northern Goiás, Brazil.
Colluvial Xenotime and Monazite

Xenotime

Monazite

Serra Verde, Goiás, Brazil
Bench Scale Physical Processing

• The evaluation and ranking of REE and Y occurrences for mineral processing is a vital part of estimating the economic viability of a deposit.

• A bench scale processing study should include rock crushing for the liberation of mineral grains followed by magnetic and gravity separation procedures.

• The ease of which a mineral concentrate can be achieved should be ranked in comparison with REE deposits that currently feed the market place.

• These tests should be performed by geologists that have hands on experience with the petrology, mineralogy and mineral chemistry of REE deposits both in the field and in the laboratory.

• The data achieved in this exercise can then be passed on to processing laboratories that utilize automated high technology instrumentation for mineral processing.
When a particular potential REE occurrence is being promoted statements are often given pertaining to the success made in a mineral processing concentration effort. In such cases REE concentrates may be reported in ranges between 40 – 90 wt. % REE. The significance of these efforts can only be measured when the cost in producing the concentrate can be found to compete with REE sources which currently feed the market place.
Exploration Targets for Y and HREE

- Xenotime – Placers, Granites, Metamorphics
- Eudialyte and Alkali-zirconosilicates (AZS)
- Rafinates
- Complex fine-grained minerals in peralkaline granitic and syenitic complexes
- Rare heavy mineral niobates with Y and HREE
- South China Clay type ion-adsorbed REE, exclusive of China
Major Requirements

Assuming a favorable political climate and good logistics, conditions determining the viability of REE deposits that can compete in the world market are as follows...

• Mineralogy and favorable lanthanide distribution
• Grade and tonnage
• Amenability to mining and mineral processing at low costs, and successful chemical cracking of the individual lanthanides for their isolation
• Acceptable low values of accompanying thorium, uranium and other deleterious impurities
• Minimum impact on the environment

Any lower production costs can significantly reduce the grade requirements
As a final statement it should be emphasized...

- Deposits containing as much as 5 wt. % LREE must compete with Bayan Obo, Maoniuping, and Mountain Pass which have much higher grade, and have established physical and chemical processing plants.
- Deposits that are mineralized with allanite and LREE-enriched apatite cannot compete economically with Mountain Pass and Bayan Obo.
- Although ion-adsorbed REE in clays from South China provide the bulk of HREE to the market place, in other countries, high costs for labor and necessary supplies, power costs, and environmental restrictions may render similar deposits uneconomical.