A Review of the Global Supply of Rare Earths

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Occurrences of rare earths
  - Geological settings
  - Main ore minerals

Review of historical and current rare earth supply
  - Pre-1990s
  - Post Chinese dominance (1990-Present)
  - Current production and progress of exploration

Future supply of rare earths
  - Availability of rare earths in China
  - Recycling
  - Forecast supply
Rare Earth Occurrences
The Light and Heavy rare earth elements

LREEs

Mainly as REE$_2$O$_3$ (except for CeO$_2$)
Geological Setting

- Acidic/Alkaline igneous intrusives, carbonatites and associated hydrothermal deposits:
  - Mountain Pass (USA)
  - Mount Weld (Australia)
  - Bayan Obo (China)
  - Aràxà (Brazil)
  - Lovozersky (Russia)

- Secondary placer/beach sand deposits:
  - India Rare Earths
  - Malaysia/Australia/Thailand/USA

- Ion absorption clays:
  - Southern China
  - Tantalus RE (Madagascar)
  - Burma??
## Major LREE Minerals

<table>
<thead>
<tr>
<th>Ore type</th>
<th>TREO%</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bastnaesite</td>
<td>1-8%</td>
<td>High REO content, Previously processed economically</td>
<td>Typically occurs in carbonates which can increase reagent consumption during processing. Mainly contains LREEs (La &amp; Ce)</td>
</tr>
<tr>
<td>Monazite (primary and placer deposits)</td>
<td>0.5-10%</td>
<td>Weathered monazite particularly high REO contents and reduced Th &amp; U, Developed processing method</td>
<td>Often occurs along with U and Th minerals.</td>
</tr>
<tr>
<td></td>
<td>(0.5-2.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loparite</td>
<td>2-3%</td>
<td>Developed processing method, Titanium content</td>
<td>Significant Th and U content in ores, Mainly contains LREEs</td>
</tr>
</tbody>
</table>
## Major HREE Minerals

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<thead>
<tr>
<th>Ore type</th>
<th>TREO%</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion absorption clays</td>
<td>&lt;0.5%</td>
<td>Well established main source, easy to process, Low cost</td>
<td>TREO content, environmentally damaging mining techniques</td>
</tr>
<tr>
<td>Eudialyte (RE Silicates)</td>
<td>~0.5-1.5%</td>
<td>Favourably contains HREEs</td>
<td>Hard rock deposits requiring more processing stages, high reagent consumption, No widely established metallurgical process</td>
</tr>
<tr>
<td>Xenotime</td>
<td>1-2%</td>
<td>High yttrium content, Established process</td>
<td>Deposits of “pure” xenotime are quite unusual and are often small. Some deposits have significant levels of Th and U</td>
</tr>
<tr>
<td>Uranium tailings</td>
<td>~5%</td>
<td>Material already mined reducing overall mining costs</td>
<td>Composition variable, Y levels may be low, capacity limited by amount of tailings generated</td>
</tr>
</tbody>
</table>
Rare Earth Supply
Pre 1990s – Mountain Pass, USA

Prior to the 1990s, the Mountain Pass mine in California, USA was the largest supplier of REs to the global market.

Source: MLR, MIIT, NDRC, CREIC, Company reports, Roskill estimates
Post 1990 – Chinese dominance

- Increased production as a by-product of iron ore mining in Inner Mongolia (Baotou Steel RE)

- Numerous small scale and artisanal mining projects in southern China became an important source of HREOs

- China’s dominance of the rare earths market was not a concern to the ROW until the mid-late 2000s, as rare earth export quotas tightened and there was little ROW production to fall back on

- By 2005, China accounted for 96% of global rare earth production, including 99.8% of HREO production

- Chinese dominance of REE production peaked in 2008 accounting for 97% of global production
Where are the Chinese Production Centres?
Where are the Chinese Production Centres?

LREO (2012)
- Southern District: 69%
- Northern District: 20%
- Western District: 11%

HREO (2012)
- Southern District: 91%
- Northern District: 7%
- Western District: 2%

Source: Roskill estimates
China – Northern RE District

- Comprises rare earth companies within Inner Mongolia Autonomous Region and Shandong province

- Inner Mongolia Baotou Steel Rare-Earth (Group) Hi-Tech Co. is the largest producer of REs in the northern district.

- Estimated production in 2012 equalled 62% of Chinese production

- Production quota in 2012: 51,500tpy REO

- Production is predominantly LREEs
China – Western RE District

- Western District includes rare earth producers in Sichuan province at seven mining licences.

- Sichuan Jiangxi Copper Rare Earths Co. is the largest producer from the Maoniuping mine. Other mining licences holders are:
  - Mianli Rare Earths Refining Plant,
  - Sichuan Mianning Mining Industry
  - Sichuan Mianning Yinshan RE Mining & Refining Plant
  - Diaoloushan Rare Earths Mine
  - Sichuan Hanxin Mining Development
  - Xichang Zhineng Industry

- Estimated production in 2012 totalled 10% of Chinese production.

- Production quota in 2012: 24,400t REO

- Predominantly light rare earths.
China – Southern RE District

- Southern district includes Jiangxi, Guangdong, Fujian, Hunan, Guangxi and Yunnan

- Major producing companies:
  - China Minmetals RE (Fujian, Hunan, Guangdong)
  - Ganzhou RE Group (Jiangxi)
  - Chinalco (Guangdong, Guangxi)
  - Guangdong Rare Earth Industry Group (Guangdong)
  - China non-Ferrous Metals (Jiangxi, Guangdong)

- Estimated production in 2012 totalled 27% of Chinese production

- Production quota in 2012: 17,900t REO

- Source of >90% of global HREE production in 2012
Mine Production outside China in 2013
Production outside China

Forecast ROW production 2013 (t REO)

24,000t REO

46% China
25% ROW
4% USA
11% Australia
1% Kazakhstan
13% India
25% South Africa
4% Russia

Source: Roskill estimates
Production outside China

- To date, successful companies have been those which are affiliated with chemical companies:
  - Molycorp (Silmet, Neo Material Technology)
  - Lynas Corp. (Solvay/Rhodia)
  - SARECO (Sumitomo)
  - Great Western (Ganzhou Qiandong RE Group)
  - Alkane (Shin-Etsu)

- Hydrometallurgy is complex, especially to produce high purity separated rare earth oxides, carbonates, chlorides, etc…
On-going exploration

- There were >200 projects exploring for rare earths outside of China at the end of 2012.
- Majority of exploration projects are located in Canada, although projects are being explored in Angola, Argentina, Ireland, USA, Australia, etc...
- Market demand could potentially sustain 6-8 new rare earth producers by 2018, mainly HREE exploration projects.
- A lack of debt and equity finance and falling RE prices in 2012 has driven some exploration companies to focus on by-product production of REs or abandon RE exploration completely.
Rare earth metallurgy

**Mining**
- Open pit
- Underground
- In-situ

**Milling**
- Crushing & grinding
- Mixing

**Physical separation**
- DMS (loparite, monazite)
- Magnetic/electrostatic separation (Fe/Ti impurities)
- Flotation (bastnaesite, monazite)

**Cracking and Precipitation**
- Acid digestion
- Alkaline cracking (monazite)
- Heating
- Precipitation (Na$_2$SO$_4$, CaCO$_3$, Oxalic acid)

**RE Separation**
- Solvent extraction
- Ion absorption
## LREE Development Projects

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<tbody>
<tr>
<td>Arafura</td>
<td>Australia</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td></td>
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<tr>
<td>Lavreco</td>
<td>Vietnam</td>
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<td>Greenland ME</td>
<td>Greenland</td>
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<tr>
<td>Frontier</td>
<td>South Africa</td>
<td></td>
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<tr>
<td>GWMG</td>
<td>South Africa</td>
<td></td>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td></td>
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<tr>
<td>RE Resources</td>
<td>USA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Peak Resources</td>
<td>Tanzania</td>
<td></td>
<td></td>
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<tr>
<td>Montero</td>
<td>Tanzania</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td></td>
</tr>
<tr>
<td>GeoMega</td>
<td>Canada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Q1</td>
</tr>
<tr>
<td>MBAC</td>
<td>Brazil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Roskill estimates, Company reports
## HREE Development Projects

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</thead>
<tbody>
<tr>
<td>Alkane</td>
<td>Australia</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Avalon</td>
<td>Canada</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Matamec</td>
<td>Canada</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Quest</td>
<td>Canada</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Tasman Metals</td>
<td>Sweden</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Ucore</td>
<td>USA</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Northern Min.</td>
<td>Australia</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Stans Energy</td>
<td>Kyrgyzstan</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Tanbreeze</td>
<td>Greenland</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
</tbody>
</table>

Source: Roskill estimates, Company reports
Future Supply of Rare Earths
Where will future supply come from?

- Primary production from mines
  - China
  - ROW

- Recycling or Urban Mining
  - Phosphors - Umicore/Rhodia
  - Magnets - Hitachi, Mitsubishi and Showa-Denko
  - Polishing powders - Asahi Glass
Where will future supply come from?

- China will account for an estimated 74% of global RE production in 2015.

- Chinese dominance is set to fall to 61% by 2018, but supply from the ROW will have a much larger impact on LREEs than on HREEs.

Source: Roskill estimates
Where will future supply come from?

Source: Roskill estimates
Will RE availability in China affect supply?

- Some deposits in Ganzhou, Jiangxi province may have a limited mine life of 15-20 years
- REE content of ores at Baotou expected to decline as pit migrates west

**BUT**

- Since mid-2011, the 2008 ban on new mining licences was partially lifted to allow new mines in Fujian, Hunan and Guangxi
- Reserves of ion adsorption clays in Guangxi total 6.7Mt, a further ~3.2Mt have been identified in Fujian and reserves of 0.6Mt REO of ion absorption clays in Jiangxi were reported at the end of 2012
- Baotou estimated to contain reserves of 28.8Mt REO, enough to maintain production of 50,000tpy REO (production quota) for over 500 years

**EXPLORATION**

- China Minmetals is setting up a joint venture in the far west of Yunnan province to develop rare earth resources
- Next stop Burma? Just over the border from deposits in Yunnan, and Minmetals are being directed to review and develop overseas resources
# Recycling

<table>
<thead>
<tr>
<th>Process</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphors</td>
<td>Rhodia’s plant at La Rochelle has a capacity to process 1,000tpy phosphor powder, not necessarily all RE phosphors. REs form a minor portion of output and the process is not yet economically attractive.</td>
</tr>
<tr>
<td>Magnets</td>
<td>Currently no commercial recycling of ‘old’ scrap, although processes are being developed to process RE magnets from hard disk drives. Recycling of ‘new’ scrap produced during magnet manufacturing has been undertaken for some years now.</td>
</tr>
<tr>
<td>Polishing Powders</td>
<td>Powders are collected and reused internally at the majority of plants outside China. The availability of RE polishing powders in China has reduced installation of recycling circuits. Glass technology has also led to a decline in demand</td>
</tr>
</tbody>
</table>
Where will future supply come from?

- China will remain the dominant supplier of REs until beyond 2018.

- Strong growth in ROW supply is expected, predominantly from the ramp up and expansion of projects in the USA and Australia, but also from new projects entering production.

- Recycling is not expected to be a major source of rare earth until a scheme to collect RE magnets and phosphors over a large catchment area is implemented.
# Rare Earth Criticality

<table>
<thead>
<tr>
<th>Element or Element Group</th>
<th>Symbol</th>
<th>Relative Supply Risk Index</th>
<th>Leading Producer</th>
<th>Top Reserve Holder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare Earth Elements</td>
<td>REE</td>
<td>9.5</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Tungsten</td>
<td>W</td>
<td>9.5</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Antimony</td>
<td>Sb</td>
<td>9.0</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Bismuth</td>
<td>Bi</td>
<td>9.0</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Mb</td>
<td>8.6</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Strontium</td>
<td>Sr</td>
<td>8.6</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Mercury</td>
<td>Hg</td>
<td>8.6</td>
<td>China</td>
<td>Mexico</td>
</tr>
<tr>
<td>Barium</td>
<td>Ba</td>
<td>8.1</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Carbon (graphite)</td>
<td>C</td>
<td>8.1</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Be</td>
<td>8.1</td>
<td>USA</td>
<td>Unknown</td>
</tr>
<tr>
<td>Germanium</td>
<td>Ge</td>
<td>8.1</td>
<td>China</td>
<td>Unknown</td>
</tr>
<tr>
<td>Niobium</td>
<td>Nb</td>
<td>7.6</td>
<td>Brazil</td>
<td>Brazil</td>
</tr>
</tbody>
</table>

Is this criticality ranking warranted?

Source: BGS Risk List 2012
For more information on Roskill Consulting Group and the full range of Roskill reports, including Rare Earths & Yttrium: Market Outlook to 2015, and Lithium: Market Outlook to 2017, please go to our website www.roskill.com

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