Michael D. Campbell\textsuperscript{1}
Robert W. Gregory\textsuperscript{2}
Steven S. Sibray\textsuperscript{3} and
James L. Conca\textsuperscript{4}

\textsuperscript{1} I2M Consulting LLC, Houston, TX, and Chairman, UCOM
\textsuperscript{2} Wyoming State Geological Survey, Laramie, WY, Vice-Chair (Government), UCOM
\textsuperscript{3} University of Nebraska – Lincoln, NE, and Vice-Chair (Academia), UCOM
\textsuperscript{4} UFA Ventures, Inc., Richland, WA, Member, Advisory Group, UCOM

The AAPG Energy Minerals Division’s \textbf{Uranium (Nuclear and REE) Committee} (aka UCOM)

A \textit{YouTube version of this presentation (with narration) is also available (here)}


September 2, 2020
Topics to be Introduced:

As we summarized in our abstract for the Theme 9 Session:

- **Source of REEs:**
  - REE Distribution in universe and solar system, moon, meteorites, Earth’s crust, sea-floors, coal and lignite, and groundwater,
  - Mineralization processes on Earth, often associated with U and Th,

- **History of REE Development:** REE offer special properties for industrial applications …. Expanding use.

- **As new REE applications were developed by the academic-industrial Complex in U.S. and Overseas,**

- **Major worldwide research efforts began in early 2000s with explosion of technical papers after 2010 dealing with exploration projects, nature of REE in deposits in the U.S. and worldwide,**

- **REE demand**, mining, and prices have increased (with some pullback) as China held back price-controlled REE supplies with the REE Price Boom of the 2010-2013.

- **Other REE sources are being sought as coproducts of metalliferous mining, recycling of electronic waste, coal-lignite, waste ash, byproducts of phosphate mining, deep-sea nodules and mattes, but with some environmental concerns along supply chain.**

- **Competition in REE mining and processing depends ore grade of specific REE availability with REE demand expanding ... mine production only amounting to about 170,000 metric tons in 2018, but increased to 210,000 tons in 2019, (Rare Earth Oxides produced worldwide), and likely increase by 7% to 12% /yr in the future .... The current Pandemic notwithstanding.**
Original Sources of REE and Other Elements

• **REE** are spread all over the known universe by exploding stars:
  - Dying low-mass stars, and by
  - Merging neutron stars.

• Cosmic or solar system fingerprints: widespread REE dust? Impacted by volcanism on Earth?

• **La** through **Nd** formed more by low-mass stars than by merging neutron stars,

• **...Until Pm**, after which **Sm** to **Lu** formed more by neutron star than by low-mass stars.

• **REE** distribution in solar systems’ planet forming may depend on proximity to remains of both star types.

• Asteroid/Comet dust rains down on Earth with **REE** accumulating in sediments to groundwater, as well as in mineralized zones.

• Irregularities to the **REE** distribution are discussed later.

---

**Graphic created by Jennifer Johnson**

http://www.astonomy.ohio-state.edu/~jaj/nuclea/

**Astronomical Image Credits:**

ESA/NASA/AASNova

See Details: Johnson, et al., (2020)
The Rare Earth Elements Plus Y, Sc, Gd, but also Pm

- 14 REE plus Y and others if occurring in deposit.
- Scandium and Gadolinium also industrial targets, if present.
- Promethium (Pm) is a REE, but all isotopes are radioactive and in very low concentration. But some stars show anomalous Pm ... but now (more).
- The REE concentrations decrease from La with increasing atomic number according to Oddo-Harkins rule, where even atomic number is greater than that of adjacent elements with an odd atomic number, giving a “saw-toothed” plot.
- Based on the original relation between H and He burning (nucleosynthesis).
- $^4_2\text{He}$ is a basic building block, and so all additions produce even number elements, starting with:

$$^4_2\text{He} + ^4_2\text{He} \rightarrow ^8_4\text{Be}$$

Also see: The Geoscientist's Periodic Table
REE in Lunar Igneous Rocks, Breccia, Basalt, and Earth-Found Meteorites

- Note that all sample plots of REEs are not normalized to chondrites but use concentrations to illustrate comparative patterns.

- $R^2$ & Line values for general comparison only, not for trend analysis:
  - Ave. Earth crustal abundance
  - High-feldspar lunar basalt
  - Allende A meteorite

- Some lunar samples are enriched in REE relative to Earth crustal values toward HREE (Gd, Dy, Er, Yt)

- Lunar mining of He-3 with bulk by-product recovery of REE? Sampling?

- Meteorite REE also reflecting enriched HREE? Suggesting asteroid mining for metals and REEs? Sampling?

- “Negative” Eu anomaly indicated in some lunar samples, but not all. None obvious in meteorites
REE in Upper, Middle and Lower Continental Crust

- Major effort over years to characterize metals in lower crust, middle crust, upper crust, especially the REEs.

- Plot shows enrichment of REEs from lower crust to upper crust, with La (8 ppm to 31 ppm) to Eu, then less relative enrichment of REEs after Eu.

- Note that with Pm being radioactive and degrading to low values, it has not been included in plots, and the Pm negative anomaly is not indicated on all such REE plots.

- Note Gd-Dy... enrichment in all crustal averages and Er-Yb? Compare to lunar and meteorite REE.
REE on Atlantic and Pacific Ocean Sea Floors

- **REE on sea floor** in high concentrations and high bulk, 1,000 to 2,500 ppm,
- Deep sea still technologically difficult,
- Many counties have staked claims east, west and south of Hawaii, Scotia Sea, etc.
- And, in Indian Ocean, off Japan, all sites with environmental concerns for bottom dwellers.

**Compare to Crustal REE, etc.**

(Distribution by volcanism, meteorite "dusting")
Numerous Chinese coals have been studied for REE content,

REEs are present in amounts of Ce from 6 ppm to 300 ppm,

The Chinese research on Coal stimulated U.S. research via 28 federal grants to U.S. universities, National labs, and private environmental consultants,

All reports conclude that REEs are present in raw coal, underclay, and coal fly ash (history),

REEs are available via chemical leaching should the need arise.
REE in U.S. Coal?

- Research conducted on eastern and western coal, and Gulf Coast lignite (history)
REE in Shallow Groundwater in U.S.

- Even in the colloidal-sized particles, REE content reflects similar pattern of REE distribution.
- Shallow groundwater samples from 2 separate monitoring well locations containing high arsenic content (1,000 ppm) passing through 0.45 ug and 0.10 ug filters show REE distribution only similar to other plots.
- Plot also illustrates Eu “Floor”, as fingerprint? The colloidal nanoparticles even exhibit the REE “fingerprint”.
- REE pattern is also reflected in materials ranging from slag to sediment to groundwater (example).
- Reflects “dusting” from anthropogenic sources or past volcanism or from small meteorites.
REE Distribution in Shallow Groundwater as Nanoparticles (Colloids)

(Campbell, 2019)
Types of REE Deposits

Example Carbonatites:

Mountain Pass Carbonatite (US) (Haxel (2005))
associated with saturated to oversaturated (in SiO₂), phlogopite-rich, ultrapotassic silicate igneous rocks, whereas nearly all other carbonatites are associated with undersaturated, nephelinitic, sodic rocks.

Principal REE mineral: Bastnäsite, with REE-U-Th-bearing allanite apatite, monazite, thorite, etc.

Kola Carbonatite (Russia) (Zaitsev, et al., (2014)):
burbankite, carbocernaite, hydrous ancylite, Ca- and Ba fluorcarbonatessenchysite, bastnäsite and cordyline; in addition to oxides (ioparite), silicates (cerite), and phosphates (monazite), etc.

Peralkaline Igneous Rocks:

Bokan Mountain REE (UCORE - 2020) ...see later
Round Top REE (TMRC – 2020) ...see later
Seward Peninsula REE (Campbell, et al., 2018) ...later

Heavy Mineral Sands, REE Clays, Phosphorites, etc.
Location of REE deposits and mines containing REE of interest.

Names of REE deposits / mines

55 known REE occurrences and increasing. New discoveries of REE in Canada, Australia, Greenland, U.S., etc.

REE grades and characteristics of REE occurrences impact recovery of preferential REEs, and the associated cost of recovery down the supply line to end product (e.g. magnets, etc.).

Many deposits will only become sites for geologists’ field trips.
Typical REE Mineralization Produced in Igneous and Volcanic Environments

**Type A.**
Voluminous calc-alkaline magmatism: typically no REE enrichment

**Type B.**
Back-arc or post-collisional settings: REE enrichment by magmatic and hydrothermal processes e.g. Bastaïn-type deposits, Italian alkaline province

**Type C.**
Craton-marginal rifts: REE enrichment by magmatic and hydrothermal processes e.g. Gardar Province, Oslo Rift

**Type D.**
Intra-continental rift zone: REE enrichment by magmatic and hydrothermal processes e.g. Gardar Province, Oslo Rift

**Type E.**
Alkaline regime with HSE-bearing fluid

**Type F.**
REE On Earth's Sea Floors

Swamps, lagoons, and wherever coals & lignite accumulated.

**Type G.**
REE in Coal

Sea-Floor REE accumulations from volcanism and from space dust (?)
The Major Sources of REE: Bayan Obo, Weishan & Vicinity

- REE offered at prices underwritten by Chinese Government.
- High Grade-Tonnage REE deposits.
- Mined REE and processed oxides with increasing down-stream value-adding capacity to convert REE mine outputs to oxides, metals, alloys, and end-product magnets.

Bayan Obo Rare Earth Mines, Inner Mongolia, China
### Older REE Deposits in North America

**Size and grade of some productive and potentially productive North American rare earth deposits**

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>State/Province</th>
<th>REO (Mt)</th>
<th>REO %</th>
<th>Source</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonatite</td>
<td>USA</td>
<td>Colorado</td>
<td>2.600</td>
<td>0.42</td>
<td>Jackson and Christiansen (1993)</td>
<td>By-product of Nb</td>
</tr>
<tr>
<td>Caster (2007)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron Fill</td>
<td>USA</td>
<td>Wyoming</td>
<td>0.380</td>
<td>3.3</td>
<td>Meyer (2002)</td>
<td>Carbonatite dikes</td>
</tr>
<tr>
<td>Mountain Pass</td>
<td>USA</td>
<td>California</td>
<td>1.800</td>
<td>8.9</td>
<td>Castor and Nason (2004)</td>
<td>5% REO cut-off</td>
</tr>
<tr>
<td>Bear Lodge</td>
<td>USA</td>
<td></td>
<td>0.221</td>
<td>0.1</td>
<td>Orris and Grauch (2002)</td>
<td>By-product of Nb</td>
</tr>
<tr>
<td>Oka</td>
<td>Canada</td>
<td>Quebec</td>
<td>0.140</td>
<td>1.0</td>
<td>Orris and Grauch (2002)</td>
<td>Dike deposits, high Th</td>
</tr>
<tr>
<td>Wet mountains</td>
<td>USA</td>
<td>Colorado</td>
<td>0.062</td>
<td>0.42</td>
<td>Jackson and Christiansen (1993)</td>
<td>By-product of Nb</td>
</tr>
<tr>
<td>Hicks Dome</td>
<td>USA</td>
<td>Illinois</td>
<td>0.073</td>
<td>0.5</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Alkaline rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thor Lake</td>
<td>Canada</td>
<td>NW Territories</td>
<td>1.547</td>
<td>0.41</td>
<td>Orris and Grauch (2002)</td>
<td></td>
</tr>
<tr>
<td>Strange Lake</td>
<td>Canada</td>
<td>Labrador-Quebec</td>
<td>0.440</td>
<td>0.85</td>
<td>Richardson and Birkett (1996)</td>
<td></td>
</tr>
<tr>
<td>Laxkoeber Mountain</td>
<td>USA</td>
<td>New Mexico</td>
<td>0.004</td>
<td>0.18</td>
<td>Jackson and Christiansen (1993)</td>
<td>REO = Y₂O₃ only</td>
</tr>
<tr>
<td>Kipawa Lake</td>
<td>Canada</td>
<td>Quebec</td>
<td>ND</td>
<td>0.10</td>
<td>Richardson and Birkett (1996)</td>
<td>REO = Y₂O₃ only</td>
</tr>
<tr>
<td>Iron oxide-REE</td>
<td>USA</td>
<td>New York</td>
<td>0.160</td>
<td>1.04</td>
<td>Jackson and Christiansen (1993)</td>
<td>Apatite in mill tails</td>
</tr>
<tr>
<td>Mineville</td>
<td>USA</td>
<td>Missouri</td>
<td>0.072</td>
<td>12.0</td>
<td>Orris and Grauch (2002)</td>
<td></td>
</tr>
<tr>
<td>Pea Ridge</td>
<td>USA</td>
<td></td>
<td>0.886</td>
<td>0.36</td>
<td>Jackson and Christiansen (1993)</td>
<td>Stockwork veins</td>
</tr>
<tr>
<td>Vein</td>
<td>USA</td>
<td></td>
<td>0.199</td>
<td>0.51</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Powderhorn</td>
<td>USA</td>
<td>Colorado</td>
<td>0.035</td>
<td>2.56</td>
<td>Great Western Minerals Group (2007)</td>
<td>Allanite and apatite</td>
</tr>
<tr>
<td>Lembli Pass</td>
<td>USA</td>
<td>Idaho</td>
<td>0.003</td>
<td>1.22</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Hoidais Lake</td>
<td>Canada</td>
<td>Saskatchewan</td>
<td>0.350</td>
<td>0.21</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Diamond Creek Place</td>
<td>USA</td>
<td>Idaho</td>
<td>0.150</td>
<td>0.01</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Oak Grove</td>
<td>USA</td>
<td>Tennessee</td>
<td>0.137</td>
<td>0.09</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Idaho placer</td>
<td>USA</td>
<td>Idaho</td>
<td>0.061</td>
<td>0.01</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Hilton Head Island</td>
<td>USA</td>
<td>South Carolina</td>
<td>0.027</td>
<td>0.21</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Carnilina placer</td>
<td>USA</td>
<td>North Carolina</td>
<td>0.005</td>
<td>0.005</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Cumberland Island</td>
<td>USA</td>
<td>Georgia</td>
<td>0.027</td>
<td>0.01</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Green Cove Spring</td>
<td>USA</td>
<td>Florida</td>
<td>0.002</td>
<td>0.01</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Paleoplacer</td>
<td>USA</td>
<td>Idaho</td>
<td>0.001</td>
<td>0.009</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Elliott Lake</td>
<td>Canada</td>
<td>Ontario</td>
<td>0.075</td>
<td>2.95</td>
<td>Orris and Grauch (2002)</td>
<td></td>
</tr>
<tr>
<td>Bald Mountain</td>
<td>USA</td>
<td>Wyoming</td>
<td>0.014</td>
<td>0.12</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Phosphorite</td>
<td>USA</td>
<td>Idaho</td>
<td>0.100</td>
<td>0.1</td>
<td>Jackson and Christiansen (1993)</td>
<td></td>
</tr>
<tr>
<td>Idaho deposit</td>
<td>USA</td>
<td>Idaho</td>
<td>0.001</td>
<td>2.95</td>
<td>Orris and Grauch (2002)</td>
<td></td>
</tr>
<tr>
<td>Gallinas Mountains</td>
<td>USA</td>
<td>New Mexico</td>
<td>0.001</td>
<td>2.95</td>
<td>Orris and Grauch (2002)</td>
<td></td>
</tr>
</tbody>
</table>

Data sources: Bear Lodge, Rare Element Resources (2003); Mountain Pass, Caster (1966); Green Cove Spring, Heddick (2003); Mineville, Roeder et al. (1987); Thor Lake, Avalon Ventures (2007); Strange Lake, J. W. Reim, unpublished data. ND, no data; REE, rare earth elements; REO, rare earth oxide; TR, trace. Caster (2007).

- **Caster (2007)** described some 13 years ago selected REE mines and potentially productive REE deposits, which remains as the most detailed account available today, albeit requiring updating because new discoveries have been made since in the U.S. and Canada.

- **Mountain Pass REE part of large carbonatite complex** in California (Denton, et al., (2019)).

- **REE concentrate / ore analyses are presented above for different types of REE deposits. Note that xenotime contains Y and HREE, but very little LREE.**
NEW U.S. REE and Other CMs in Texas

- A Heap Leach Project, with REE Reprocessing Plant under construction in Denver.
- Three Revenue Streams:
  1) Low REE Grade, also Y & Sc, ..... Unusual Heavy REE Content,
  2) High Hf, Be, Ga, and Zr,
  3) Economic Sulfate By-Products, ..... Na, K, Mn, and Mg, Fe, and Al,
- Nearby rail facilities provides market access of bulk by-products,
- REE mineralization in rhyolite, with yttrofluorite, yttrocerite and bastnaesite, priorite and xenotime, with fluorite, columbite and cryolite.
- Secondary-U mineralization with Be mineralization.
- Texas under explored for REE

USA Rare Earth (2020) and Texas Mineral Resources Corp. (2019)
REE Exploration in Wyoming

- Bear Lodge deposit could rival any REE deposit in the U.S.
  - Tertiary (Paleocene-Eocene) alkalic domal intrusion
  - Sills, plugs, dikes, irregular bodies, Carbonatites
  - FMR dikes (Fe, Mn, REE) - silicates and REE minerals, esp. bastnasite
  - Mostly LREE, with some HREE
    - 18 MM tons @ 3.05% TREO (1.099 billion lbs TREO) Meas. & Ind. (1.5% cutoff grade) (as per Rare Element Resources (2020)),
    - Proposed mine, physical upgrade plant (PUG), and hydrometallurgical plant
    - Projected 45-year mine life
    - 500 tpd, 1,000 tpd after 9 years
    - ~ 200 jobs
    - Project FAQs (more).

- Other REE occurrences in Wyoming (see map)
  - Pegmatites
  - Precambrian igneous and metamorphic rocks
    - Alkalic igneous rocks
    - Carbonatites
    - Conglomerates
    - Meta-igneous and meta-sedimentary rocks
  - Sedimentary occurrences of REE associations
    - Placers and paleoplacers
    - Uranium- and phosphate-rich lacustrine rocks
    - Uranium and coal deposits
    - Numerous anomalies throughout sedimentary section

- Wyoming Under Explored REE (Sutherland, et al., (2013)), (Sutherland & Cola (2016))
Five types of REE deposits are recognized in New Mexico:

1. Veins and breccias,
2. Pegmatites,
3. Carbonatites, and
4. Cretaceous heavy-mineral, beach placer deposits

The most significant deposits in the state are found in veins and breccias although some pegmatites contain REEs (McLemore, et al., 1988).

Although many sites have been explored by prospectors over the years, no large REE reserves have been established to date.

More recent surface exploration (2010) indicates that in and around the Gallinas Mountains in Lincoln and Torrance counties, REE mineralization of potential economic interest have been reported (McLemore 2010).

In the event REE demand and prices stabilize to support development, New Mexico offers prime targets for follow-up drilling and associated investigations, especially in areas of known or suspected carbonatites and alkaline igneous rocks (McLemore 2013).
REE Exploration in Colorado

- U.S. Geological Survey has identified two locations for REE deposits:
  - The Iron Hill Carbonatite Complex near the town of Powderhorn, about 22 miles southwest of Gunnison (Van Gosen [2009]),
  - Geochemical Survey in the Iron Hill area (more) in Fremont and Custer counties

- Reported REE prospect sites with carbonatite characteristics are known in the Wet Mountains and surrounding area in south-central Colorado, i.e., Gem Park, etc.

- Colorado contains numerous sites of historical metal mineralization and mining (USGS), but only a few sites with REEs. Does this indicate a lack of detailed exploration for REEs?

- Geological Foundation for REE exploration, e.g., Cappa [1998].
REE Exploration in Idaho

- The Lemhi Pass deposit is well known for Th production as part of a NW quartzite trend that extends into far western Montana that also contains REE (IGS) and (Statz, et al. (1979)),

- The Diamond Creek vein deposits with limonite and goethite appear to contain the highest Th & REE (Long, et al., (2010), pp. 49-50), and

- REE was produced from numerous placers in the 1950s and 1960s.
REE Exploration in Nebraska

Elk Creek Carbonatite

- Discovered 1970 – Framework Geophysical Program Gravity and Magnetic Anomalies – 8 mgal and 800 gammas respectively,

- Cylindrical mass of infinite depth and radius of 5,500 ft. (1,676 m). Coring 1971 – At 630 ft. – iron-rich silicate bearing carbonate rock,

- Dolomite and ankerite with lesser amount of hematite, chlorite, phlogopite, barite, serpentine, and quartz, and

- Exploration coring by Molycorp, Cominco, and NioCorp. Found REE 0.1 to 1.86% with NbO $\ldots$ 0.1 to 0.5% (Carlson & Treves (2004)) and Pittuck, M., et al., (2014).

- Geophysical anomalies indicate the presence of dense and strongly magnetized rocks at depths below existing boreholes (Drenth (2014)).

- Some work has begun with isotopes to establish paragenesis of the REE and Nb mineralization (Campbell (2017)).
REE Exploration in Alaska

ALASKA’S RARE-EARTH-ELEMENT POTENTIAL

- Bokan Mountain REE, U, Th occurrences are well known. **UCORE** is developing as economics permit.
  - Mineral resource of 4.84 million tonnes (5.33 million tons) grading 0.601% total rare earth oxides (TREO), and Inferred Mineral Resource of 1.04 million tonnes (1.14 million tons) grading 0.604% TREO, comprised of approximately 40% heavy REEs.
  - With its unique HREE geological endowment, Bokan Mountain is the highest grade heavy REE project on U.S. soil.
  - Bokan’s ease of access for operation shipping
  - Bokan’s minimal projected development cost, and
  - The Bokan project has significant financial support by the state.

- Kachauik Mountain REE, U, and Th Occurrences also well known, now with renewed attention:
  - This prospect meets all criteria for either carbonatite and/or peralkaline igneous occurrences of REEs.
  - Also serves as potential U source for adjacent basin occurrence of “roll-front” uranium deposited in Paleocene basin containing reported lignite and reported roll-front U occurrence nearby (more).
The Kachauik Mountain Cretaceous REEs occur within igneous rocks, south-eastern border of the McCarthy Basin, a possible impact crater some 30 miles in diameter?

U-Th-REE occurs in phonolite dikes along the margins of syenite country rock containing allanite and accessory minerals, i.e., monazite, sphene, etc.

U-REE occupies lattice or inter-lattice positions within separate uranium-bearing phases as minute inclusions within essential, varietal, and accessory minerals,

REE exhibits unusual Eu-Gd-Tb-Dy-Ho-Er anomaly (or fingerprint),

New road into area will make operation and development available to nearby port.
REE in Sediment of Surrounding Areas, Seward Peninsula, Alaska

- Geochemical Survey of REE in Area by USG and consultants around REE mineralization, shows anomalies.

- Graphic shows how widespread REE are in sediments derived from igneous rocks in 100 sq. mile area around mineralized zones.

- Ce dominates REE group, with decreasing concentrations of La, Nd, Pr, etc., in mineralized zones.

(Campbell, et al., (2018))
Australia REE Mines and Deposits

- Single REE mine at Mount Weld (WA), 2200 tpa;
- Monazite from mineral sands mines not extracted or exported;
- Large REE resource known at the Olympic Dam U deposit, but REE resource as secondary recovery when prices increase.
- Numerous REE-only deposits at early stage of production (e.g. Browns Range), or in feasibility studies (e.g. Nolan’s Bore, Toongi, etc.)
- Numerous REE deposits drilled and under economic evaluation (see grade-tonnage plot).
- Note in G-T plot the numerous occurrences of both carbonatite and peralkaline/alkaline with REEs in Australia
- China attempting to buy up competition in Australia and elsewhere.
- Very favorable resource development supported by state and federal governments in Australia.

Spangler, et al., (2020)

(Mudd, et al., 2018)
Greenland, Scandinavian & Russian REE Exploration and Deposits

- Greenland’s REE, U, and Th Deposits are underdevelopment,
- Exploration has indicated numerous additional REE prospects,
- For History (more).

Norway, Sweden, & Finland have significant REE deposits (Machacek and Kalvig 2017).

Selected REE deposits in the Russian Kola Province (Zaitsev, et al., 2014)
Summary of REE Development

- **Technology Development:**
  - Geoscience Research,
  - Geoscience Discovery,
  - More Research, and
  - Industrial Applications

- **Industrial Development Stages:**
  - REE Exploration / G-T Evaluations,
  - Product Demand,
  - Resource Price,
  - Economic Pressure, and
  - Geopolitical Interaction

- **Employment Potential**
  - Academic Preparedness,
  - Jobs in U.S. ([more](#)),
  - Jobs in Australia ([more](#)),
  - Jobs in UK ([more](#)).
The 2011 price bubble stimulated many REE projects throughout the world, for example Dy price rise and China controls.

Australia looked back at all REE prospects in their government records and began:

- exploration via geochemical and geophysical surveys,
- followed by drilling and sampling of anomalies,
- followed by G-T calculations, and
- followed by economic studies.

Rest of world also re-looked at REE prospects in their countries ... Until the REE began to fall back.

Demand-Price conditions remain fluid.

1 Chinese yuan per kilogram = 0.14101 U.S. dollars/kg TODAY

or for 20,000 kilograms of Dysprosium in 2011 = US$ 2,820.20

Peak of 2011 rare earth bubble

Prices are up 63% so far in 2019
Industrial Use of REE and Critical Elements

Additional Elements Having Special Applications

Light REE:
- La = Lanthanum
- Ce = Cerium
- Pr = Praseodymium
- Nd = Neodymium
- Sm = Samarium

Heavy REE:
- Eu = Europium
- Gd = Gadolinium
- Tb = Terbium
- Dy = Dysprosium
- Ho = Holmium
- Er = Erbium
- Tm = Thulium
- Yb = Ytterbium
- Lu = Lutetium
- Y = Yttrium

1. Neodymium, Dysprosium, Terbium and Europium in highest demand = Magnets of all types, shapes and sizes.
2. Cerium not “rare” (25th @ ave. 60 ppm in crust); Tm & Lu least of REEs at <1 ppm).
3. REEs often associated w/ U and Th, and many REEs are more abundant than Au and Ag.
4. World Reserves of REEs increases with increasing exploration, like U and most other natural resources.
5. Market dynamics, > research & investment in alternatives will ultimately determine the criticality of elements.
REE World Production and Distribution

World REE Mine Production – 2018: 170,000 tons to 210,000 tons REO in 2019,

China produced ~ 71% and increasing, but illegal mining still exists,

Vietnam has reported REE reserves located near the border with China,

U.S. production from re-started Mountain Pass deposit, California in 2019 increased to 26,000 tons,

Australia has numerous REE projects and outstanding support from state and federal governments.

Australian deposits 2nd in the world of REE resources in comparison with other resources, but environmental considerations come into play.

All REE mine production and sale of ore depends primarily on:

- characteristics of particular ore (G-T),
- type of mineralogical assemblage in ore, and
- type of ore processing required to meet buyers demands for subsequent refining into specific REE metals, etc.

Source: USGS - Statistica

** REE production coming China border? *** Bastnaesite, a rare-earth fluorocarbonate mineral, mined as a primary product at a mine in CA.
A primary reason China has dominated the REE industry is because it has deposits with high grade and very large reserves of REEs, now market chain support.

The other principal REE deposits: (Russia: Lovozero, Australia: Mt. Weld), and the American deposit Mountain Pass has high G-T reserves, which determines the economic value of only a few deposits to date, although other deposits may come into play in the future, e.g. LREE vs. HREE, etc., (History and Discoveries).
## REE Use and Price Over Time

Rare-earth oxide industry uses and market prices.*

<table>
<thead>
<tr>
<th>Metal Oxide</th>
<th>Principal Uses</th>
<th>Price US$/kg October, 2008</th>
<th>Price FOB China July, 2019</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanthanum oxide 99% min</td>
<td>Rechargeable batteries</td>
<td>8.50 – 9.00</td>
<td>$1.68</td>
<td>$3.30</td>
</tr>
<tr>
<td>Cerium oxide 99% min</td>
<td>Catalysts, glass, polishing</td>
<td>4.70 – 4.90</td>
<td>$1.90</td>
<td>$1.90</td>
</tr>
<tr>
<td>Praseodymium oxide 99% min</td>
<td>Magnets, glasses colorant</td>
<td>31.80 – 32.70</td>
<td>$54.50</td>
<td>$41.20</td>
</tr>
<tr>
<td>Neodymium oxide 99% min</td>
<td>Magnets, lasers, glass</td>
<td>32.50 – 33.00</td>
<td>$44.00</td>
<td>$44.00</td>
</tr>
<tr>
<td>Samarium oxide 99% min</td>
<td>Magnets, lighting, lasers</td>
<td>4.25 – 4.75</td>
<td>$1.83</td>
<td>$1.83</td>
</tr>
<tr>
<td>Europium oxide 99% min</td>
<td>TV color phosphors: red</td>
<td>470.00 – 490.00</td>
<td>$33.50</td>
<td>$30.50</td>
</tr>
<tr>
<td>Terbium oxide 99% min</td>
<td>Phosphors: green magnets</td>
<td>720.00 – 740.00</td>
<td>$575.50</td>
<td>$650.00</td>
</tr>
<tr>
<td>Dysprosium oxide 99% min</td>
<td>Magnets: lasers</td>
<td>115.00 – 120.00</td>
<td>$270.50</td>
<td>$262.00</td>
</tr>
<tr>
<td>Gadolinium oxide 99% min</td>
<td>Magnets, superconductors</td>
<td>10.00 – 10.50</td>
<td>$28.46</td>
<td>$19.70</td>
</tr>
<tr>
<td>Yttrium oxide 99.99% min</td>
<td>Phosphors, ceramics, lasers</td>
<td>15.90 – 16.40</td>
<td>$3.60</td>
<td>$3.10</td>
</tr>
<tr>
<td>Lutetium oxide 99.99% min</td>
<td>Ceramics, glass, phosphors and lasers</td>
<td>Up to 2,000/kg</td>
<td>$618.63</td>
<td>$613.42</td>
</tr>
<tr>
<td>Thulium oxide 99.99% min</td>
<td>Superconductors, ceramic magnets, lasers, x-ray devices</td>
<td>Up to 3,000/kg</td>
<td>n/a</td>
<td>$180.00-$360.00</td>
</tr>
</tbody>
</table>

REEO Prices and Ore Value: Changing Demands Creates Value

- During the initial REE “Bubble” in 2010 to 2012, the concept of “Basket Price” of REE ore emerged to include all REEs in the overall economic calculations of the project value.

- There are limitations to the REE Basket Price metric. To be specific, the basket price does not account for:
  1. REE Deposit grade or tonnage, a strong potential limitation for several high-basket price REE companies.
  2. The costs associated with mining, extraction and separation of REEs, a serious limitation for most REE projects in development.
  3. Mineralogy and processing level of difficulty, which varies for most REE companies.
  4. Project economics (opex, capex, IRR, NPV, etc.).
  5. Snapshot in time of market prices, otherwise variable.
  6. Some flawed economic assessments assumes 100% REO recovery from ore to final product.
  7. Assumes standardized forms and specifications of final saleable REO products, not like gold w/ an established market.


Source: Technologies Media Research, Feb 2020; Geoverso et al. 2011

Rockstone Research (2015)
REE Resource Reserves and Ore Grades Make All The Difference in Economics

REEs are currently mined from two types of geological environments…carbonatites and alkaline igneous silicates…in geopolitically diverse countries.

Future REE sources will depend on progress of REE processing/recovery research.

Fe-REE deposits with high G-T and multiple by-products will be mined.

Other REE sources in high bulk-low grade deposits as by-products recovered from phosphate mines, or from coal or coal ash waste may also be recovered.

Innovation and economics will determine the road ahead for the REEs.

General Conclusions:

- REEs are currently mined from two types of geological environments...
- Future REE sources will depend on progress of REE processing/recovery research.
- Fe-REE deposits with high G-T and multiple by-products will be mined.
- Other REE sources in high bulk-low grade deposits as by-products recovered from phosphate mines, or from coal or coal ash waste may also be recovered.
- Innovation and economics will determine the road ahead for the REEs.
**REE Future Use and Value**

**Rare earth consumption by application, 2028 (volume & value)**

- New applications,
- New REE sources,
- Prices will decline,
- Mine competition increases, HREE may dominate.

---

**REE Used:**
- **Volume**: Ce, Lu and Tm
- **Value**: Ce, Pr, Nd, Lu, La, Ce, Pr, Nd, Sm, Pr, Nd, Tb, Dy, Gd, Tm, La, Eu, Lu, Y, Tb, Ce, Pr, Nd, Sm, Eu, Dy, Y, La, Nd, Sm, Eu, Er, etc.

---

Argus Research (2019)
Historical trade routes are changing,
Change depends on demand, country, source G-T, and location of refiners,
Supply chains in flux, &
Specific REE Demand increasing (magnets, etc).

Bottom line ....
Summary:

- REEs are created during the death of certain types of stars,
- REE are distributed by large explosions that propel star fragments of REE into space becoming eventually part of new solar systems and planet formation and residual asteroids and dust,
- REEs are concentrated by geological process in mineralized zones, & residual fingerprints,
- Paradox's will continue until supplies of high-priced REE meet demand.
- Demand of some REE with be higher than others with Compound Annual Growth Rate (CAGR) of even higher than 7%.
- Current low world mine production, but huge resources.
- Development of off-world metals to include REEs (see AAPG-EMD Memoir 101)?
- It’s all about the cost of REE mine production, etc.
References


Argus Research, 2020, Research on Rare Earth Usage and Value, URL: https://www.argusresearch.com/


Borzykowski, B., 2019, Wyoming May Hold the Key to the Rare Earth Minerals Trade War with China, URL: https://www.cnbc.com/2019/07/10/wyoming-may-hold-key-to-the-rare-earth-minerals-trade-war-with-china.html

Brown Range REEs Halls Creek Shire, Western Australia, Australia: https://www.mindat.org/loc-289721.html


Campbell, M. D., 2019, REE in Groundwater, Confidential Investigations, I2M Consulting, LLC, Houston, Texas.

Campbell, E. M., 2107, Sulfur Isotope Variations in the Elk Creek Carbonatite Complex, Southeastern Nebraska, USA, University of Nebraska In Partial Fulfillment of Requirements For the Degree of Master of Science Major: Earth and Atmospheric Sciences, Faculty Advisor: Professor Richard M. Kettler, 71 p., URL: https://i2massociates.com/downloads/ElkCreekCarbonatiteCampbell_2017.pdf


Commerce Resources Corp., 2019, The Ashram Deposit Rare Earth Elements/ Fluorspar Quebec, Canada, URL: https://www.commerceresources.com/assets/pdf/Ashram%20Corporate%203%20July%202019-20190703122237.pdf
References (Continued)

I2M Web Portal Search Results: Sea-Floor Deposits: https://web.i2massociates.com/search_resource.php?search_value=Sea-Floor+Deposits#page=1


Idaho Geological Survey, GeoNote: Rare Earth Elements and Other Critical Metals in Idaho, 4 p., URL: https://www.idahogology.org/pub/GeoNotes/GN44_Rare_Earth_Elements.pdf


McLeod, C. L., and M. P. S. Krekeler, 2017, Sources of Extraterrestrial Rare Earth Elements: To the Moon and Beyond, Resources 2017, 6, 40; doi:10.3390/resources6030040, 28 p.. URL: http://www.i2massociates.com/downloads/resources-06-00040.pdf


References (Continued)


Rare Element Resources, 2020, Bear Lodge Project Wyoming. URL: https://www.rareelementresources.com/bear-lodge-project/bear-lodge-project Project FAQs: https://www.rareelementresources.com/bear-lodge-project/project-faqs

Rare Earth Elements: China's Vibrantium? URL: Video on REEs: https://www.youtube.com/watch?v=ri7FbrPPjw

Rare Earth Supply Chains: URL: http://www.uvm.edu/gee/pubpdfs/Golev_2014_Resources%2OPolicy.pdf

Roskill Research, 2020, Rare Earths: Outlooks to 2029, URL: https://roskill.com/market-report/rare-earths/

Roskill Research, 2016, Commerce Resources Well Positioned For Robust REE Demand Growth Going Forward, URL: https://seekingalpha.com/instablog/2366771-rockstone/4934218-commerce-resources-well-positioned-for-robust-ree-demand-growth-going-forward


UCORE Rare Metals, Inc., 2020, Bokan Mountain, Alaska, The Highest Grade Heavy Rare Earth Element Project in U.S., URL: https://www.ucore.com/bokan

USA Rare Earth, 2020, Round Top Mountain Project, Texas, URL: http://usarearearth.com/


