SOURCES of RARE EARTH ELEMENTS in the U.S. and the World

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The AAPG Energy Minerals Division's Uranium (Nuclear and REE) Committee (aka UCOM)

A YouTube version of this presentation (with narration) is also available (here)

AAPG-EMD On-Line Conference Theme 9 – Critical Mineral Exploation – The Next Energy Frontier

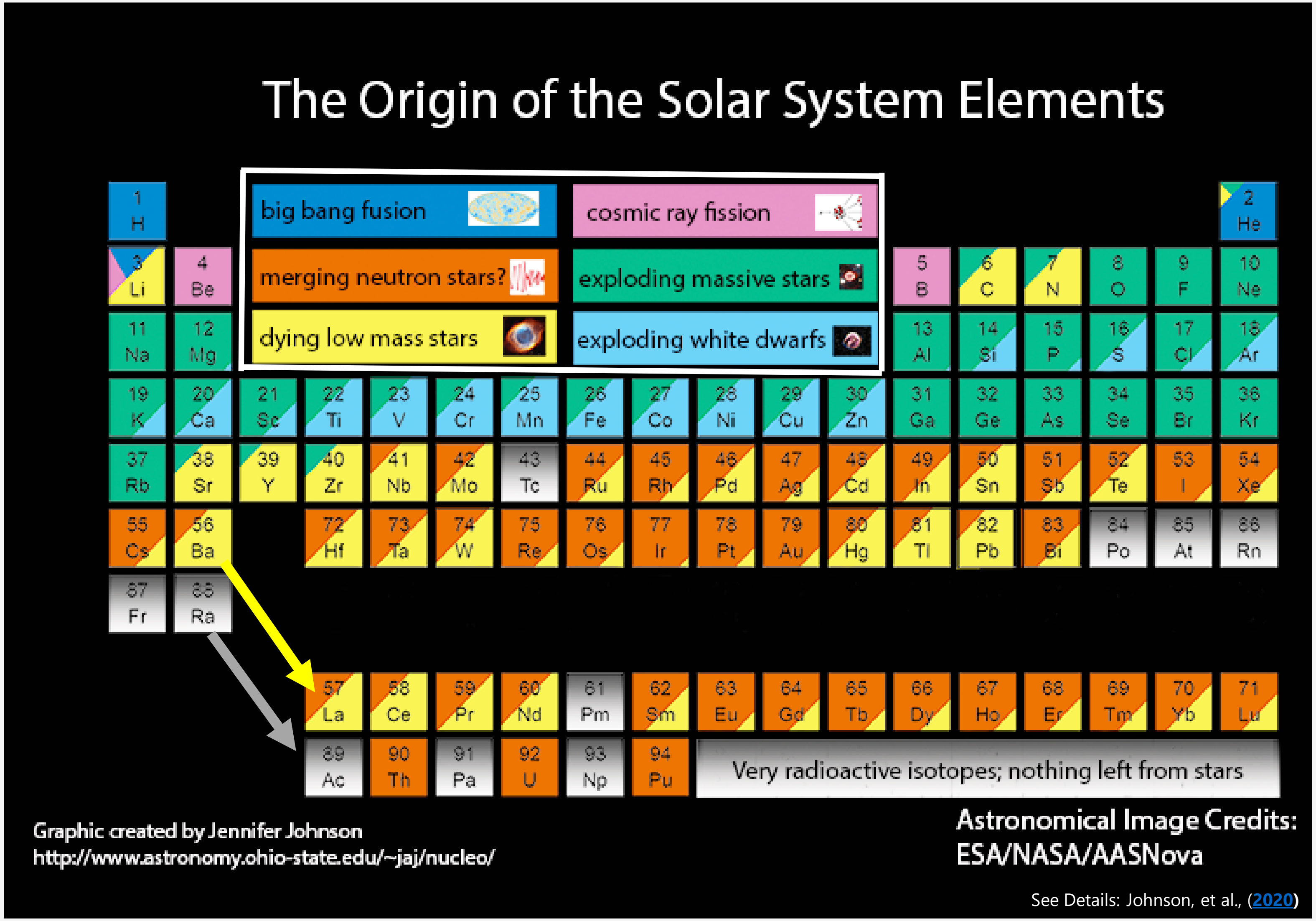
September 2, 2020

Topics to be Introduced:

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

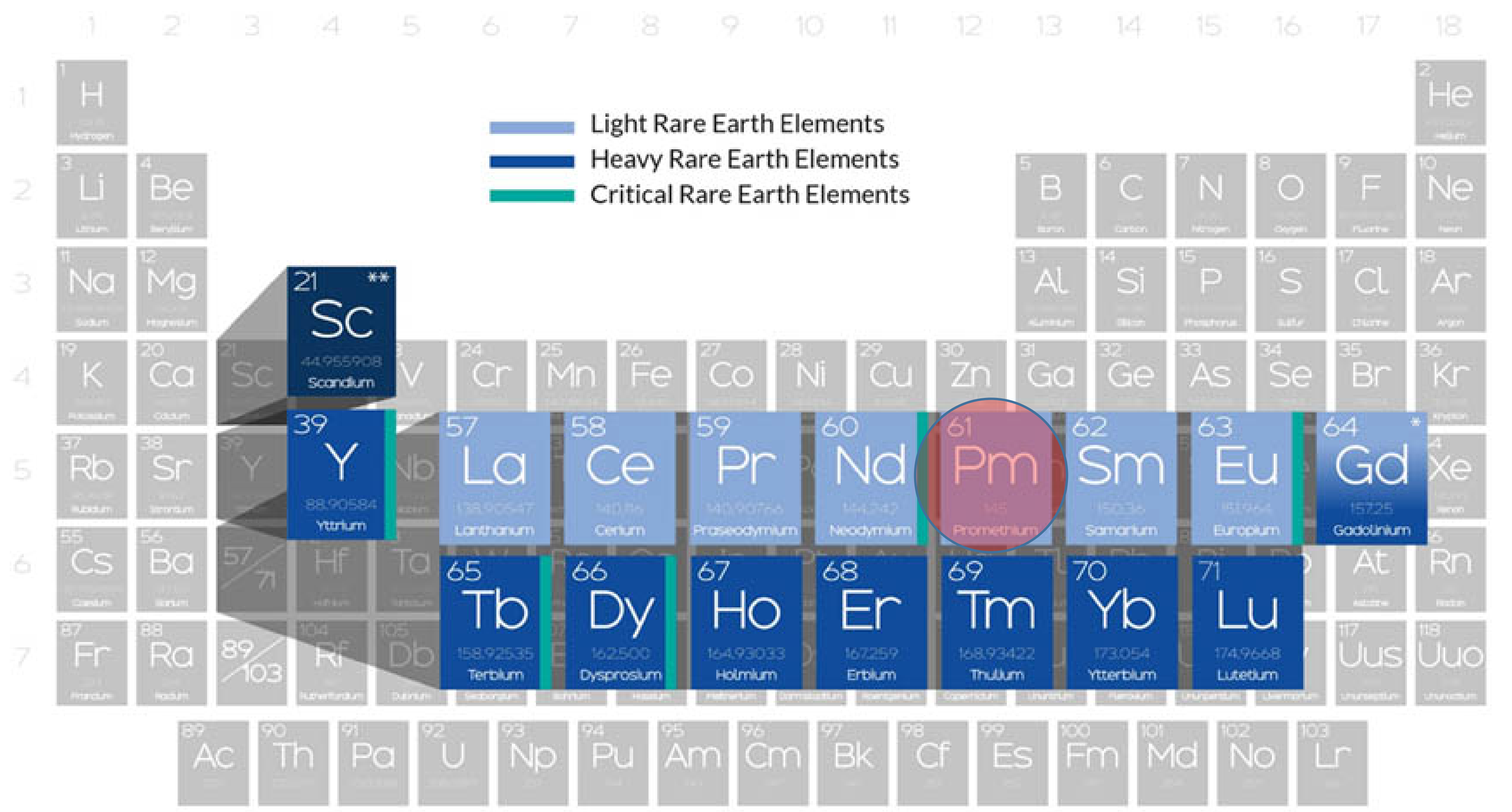
- Source of **REEs**:
  - **REE** Distribution in universe and solar system, moon, meteorites, Earth's crust, sea-floors, coal and lignite, and groundwater,
  - Mineralization processes on Earth, often associated with U and Th,
  - **REE** Deposits and Mines: China, U.S.(Texas, Wyoming, New Mexico, Colorado, Idaho, Alaska), Australia, Greenland, Scandinavia, Russia.
- 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.

The Rare Earth Elements Plus Y, Sc, Gd, but also Pm



* Gd: IUPAC Light REE; USGS Heavy REE
** Included with rare earth elements

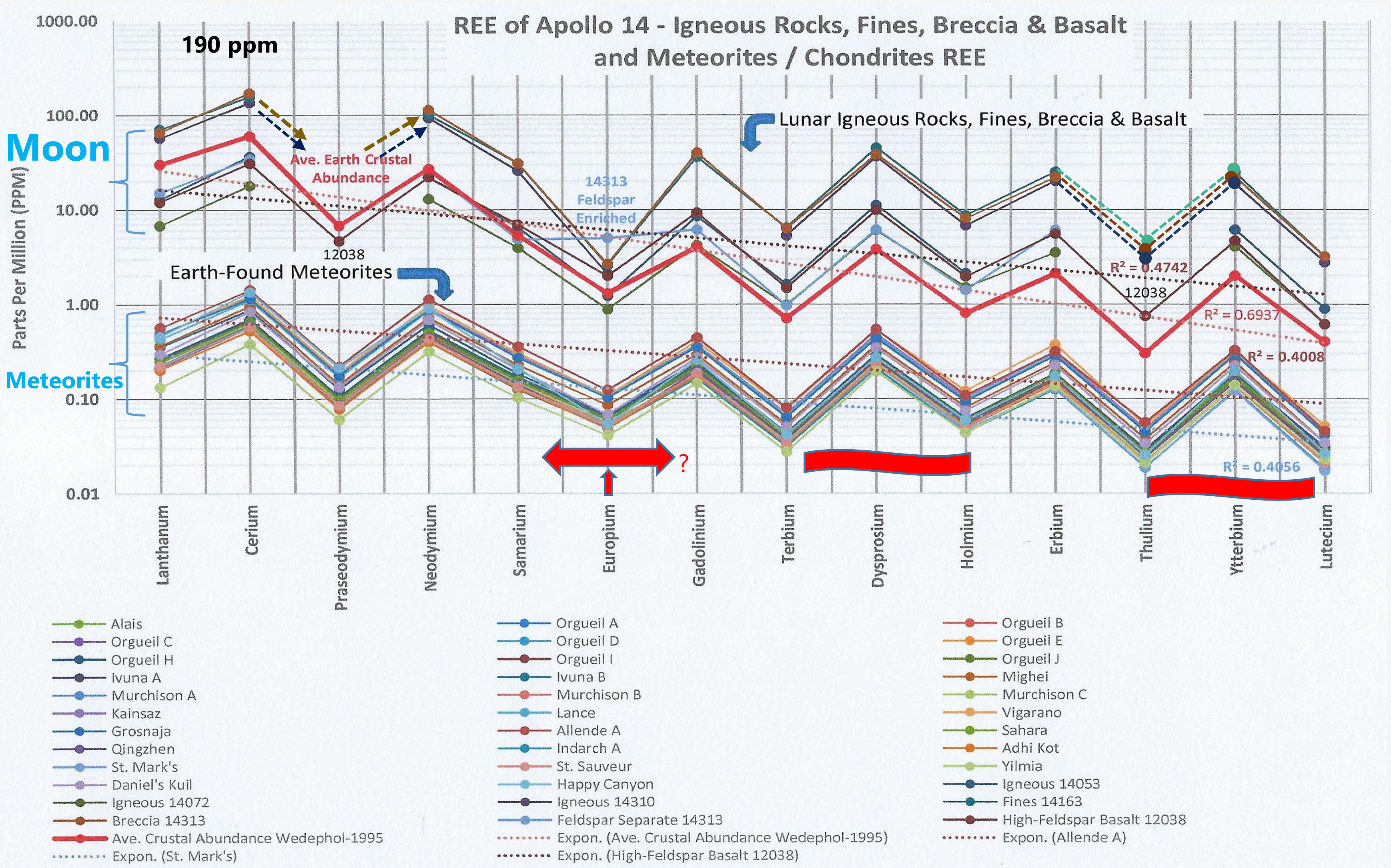
Updated Periodic Table

- 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).
- $^{4}_{2}He$ is a basic building block, and so all additions produce even number elements, starting with:

$^{4}_{2}He + ^{4}_{2}He \rightarrow ^{8}_{4}Be$; then: $^{8}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C$

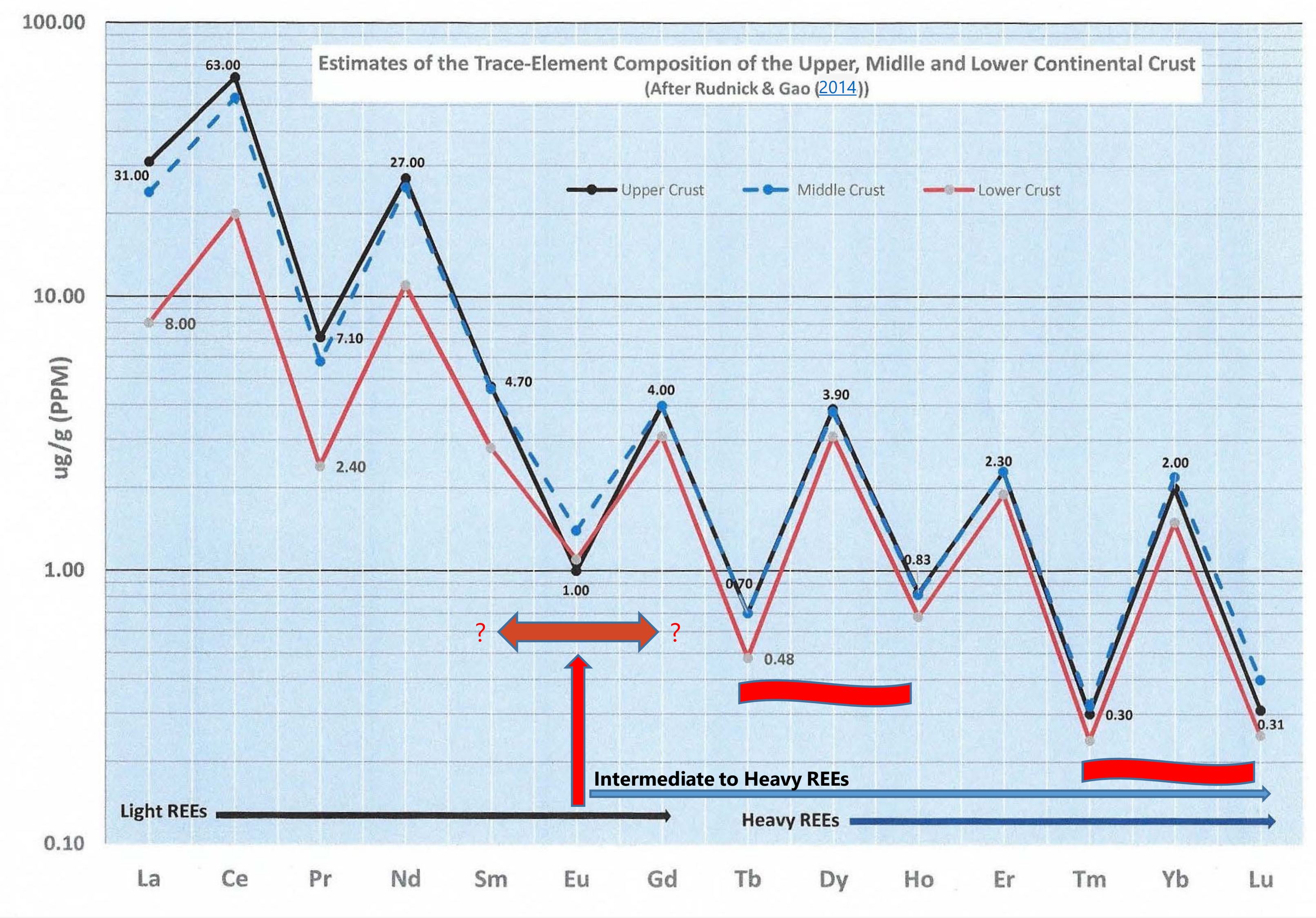
Also see: The Geoscientist's Periodic Table

REE in Lunar Igneous Rocks, Breccia, Basalt, and Earth-Found Meteorites



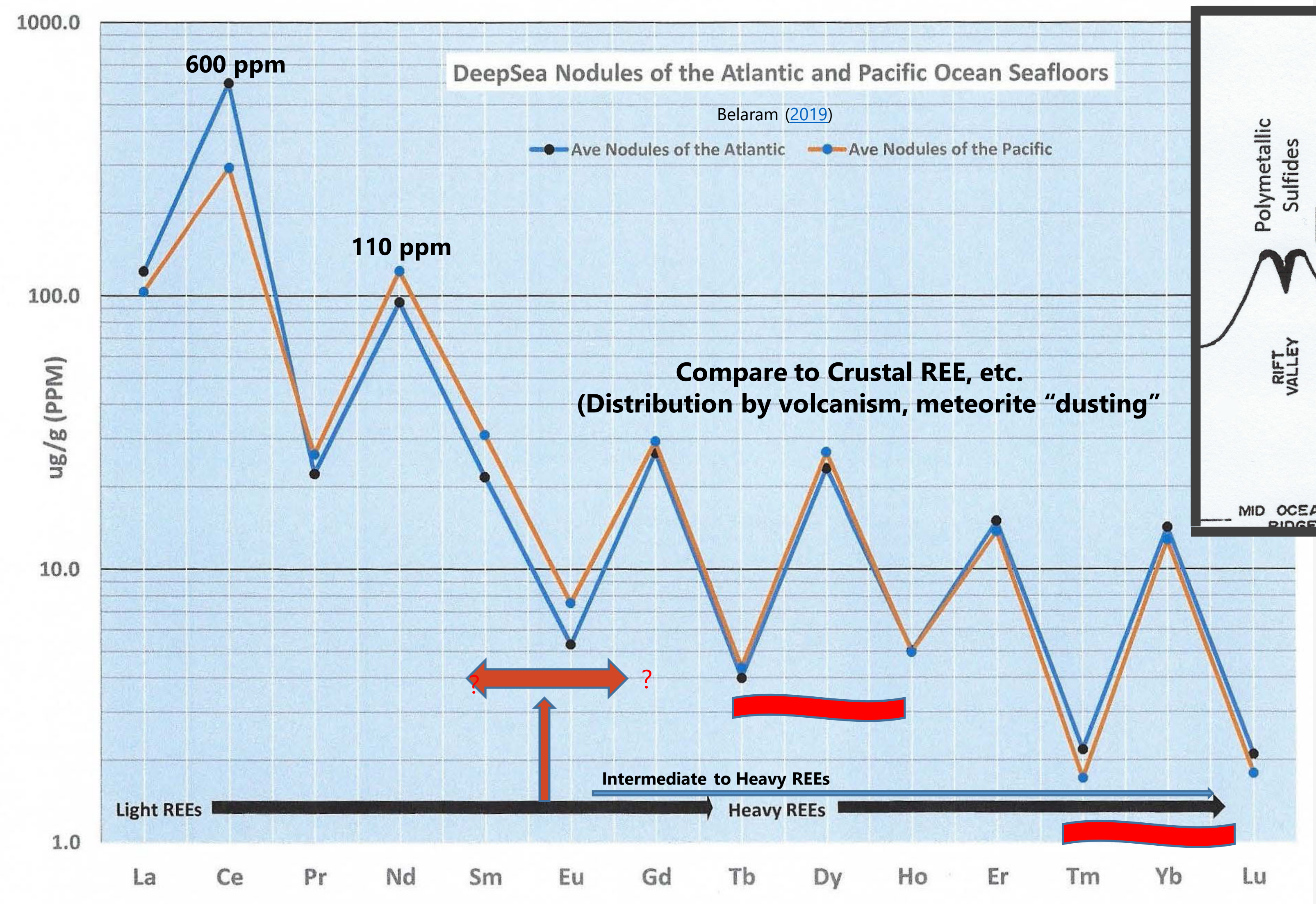
- Note that all sample plots of **REEs** are not normalized to chondrites but use concentrations to illustrate comparative patterns.
- R^2 & Line values for general comparison only, not for trend analysis:
  - Ave. Earth crustal abundance
  - High-feldspar lunar basalt
  - Allende A meteorite
- Some 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

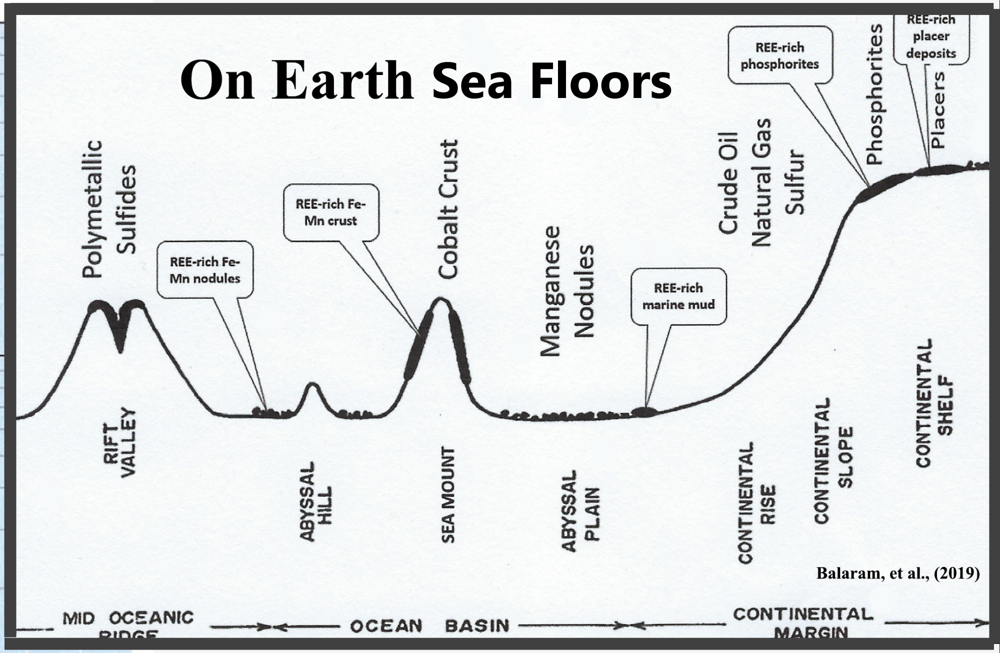
REEE in Upper, Middle and Lower Continental Crust



- 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**.

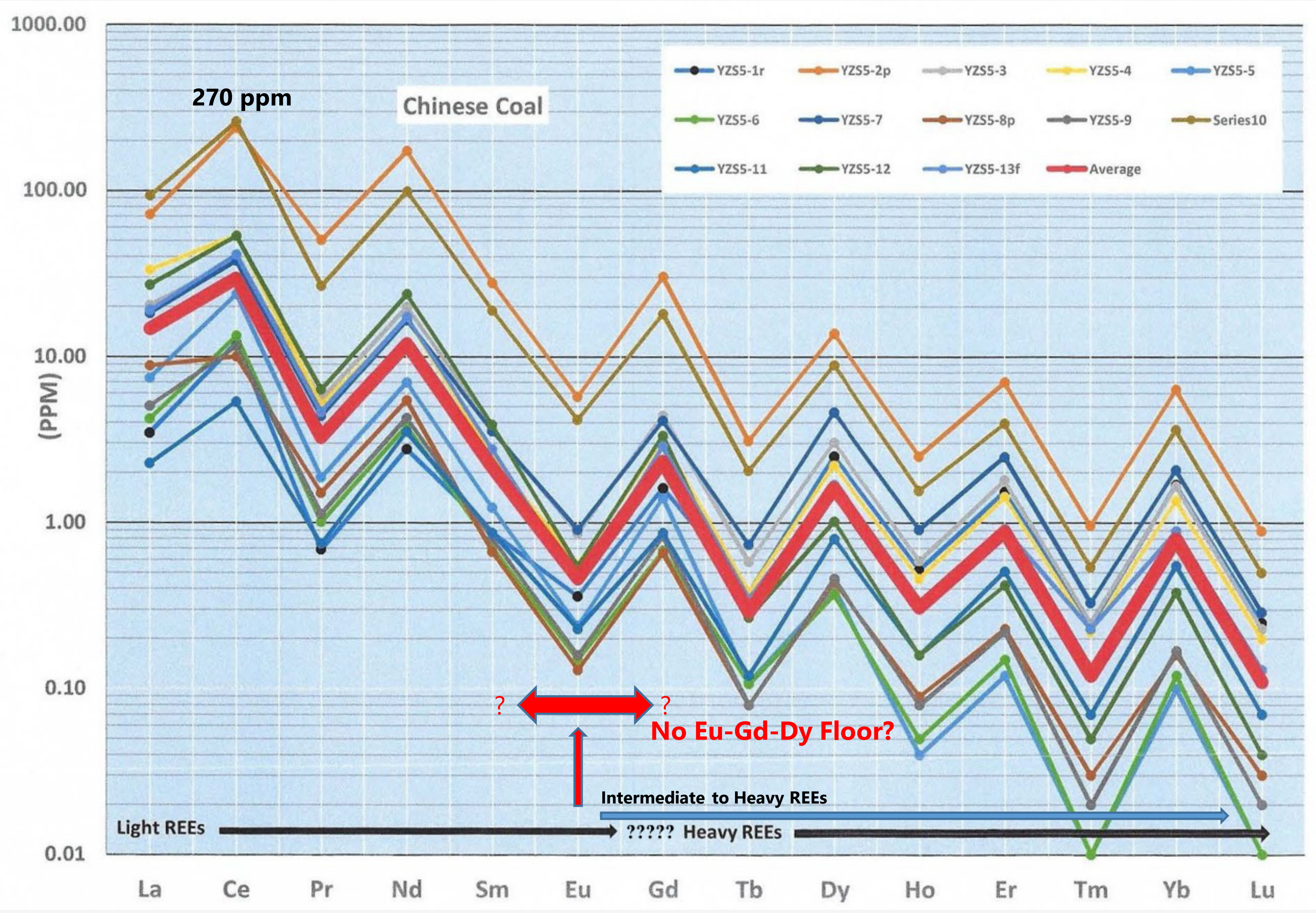
REE on Atlantic and Pacific Ocean Sea Floors





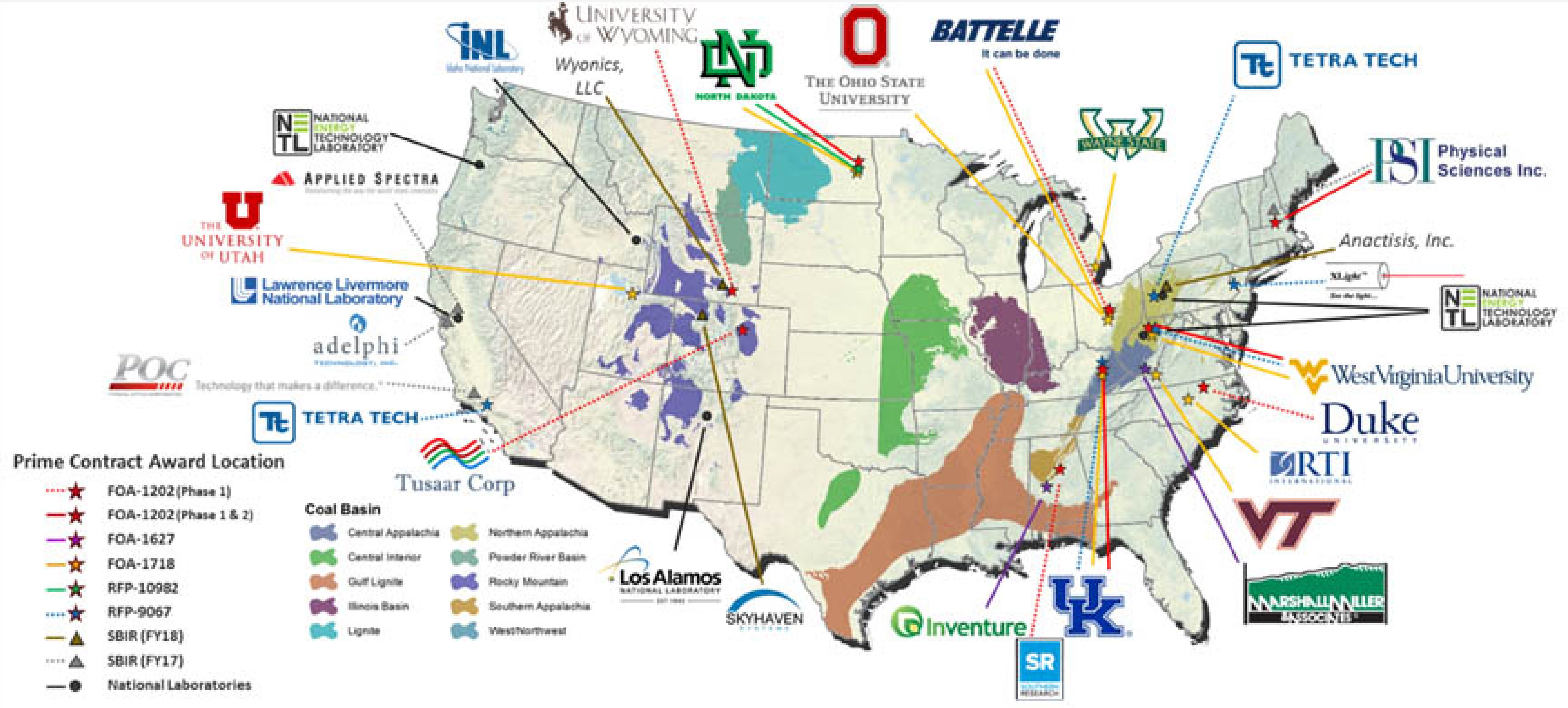
- REE on sea floor in high concentrations and high bulk,1,000 to 2,500 ppm,
- Deep sea still technologically difficult,
- Many counties have staked claims east, west and south of Hawaii, Scotia Sea, etc.
- And, in Indian Ocean, off Japan, all sites with environmental concerns for bottom dwellers.

REE in Chinese Coal



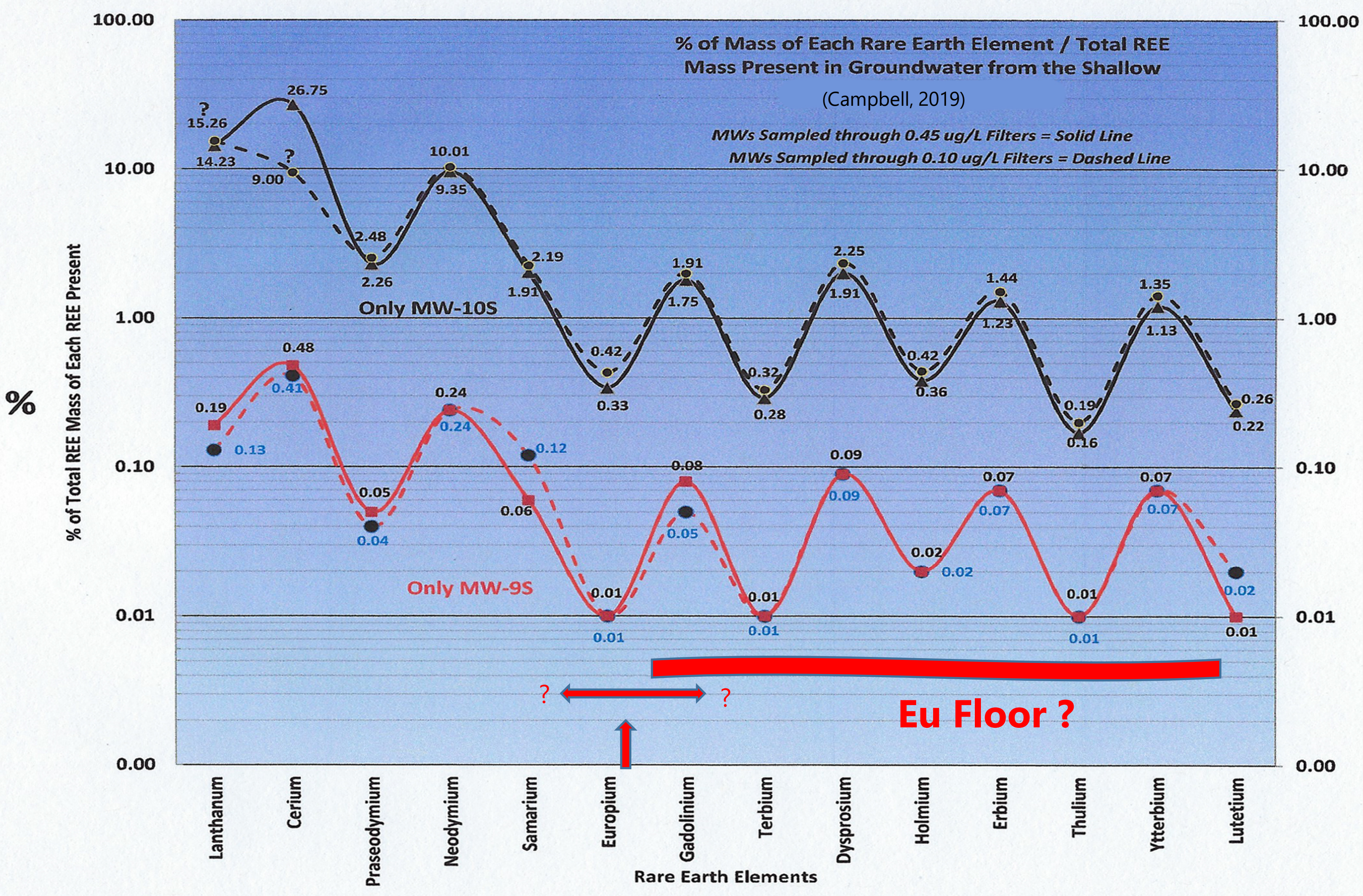
- Numerous Chinese coals have been studied for **REE** content,
- **REEs** are present in amounts of **Ce** from 6 ppm to 300 ppm,
- The Chinese research on Coal stimulated U.S. research via 28 federal grants to U.S. universities, National labs, and private environmental consultants,
- All reports conclude 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?



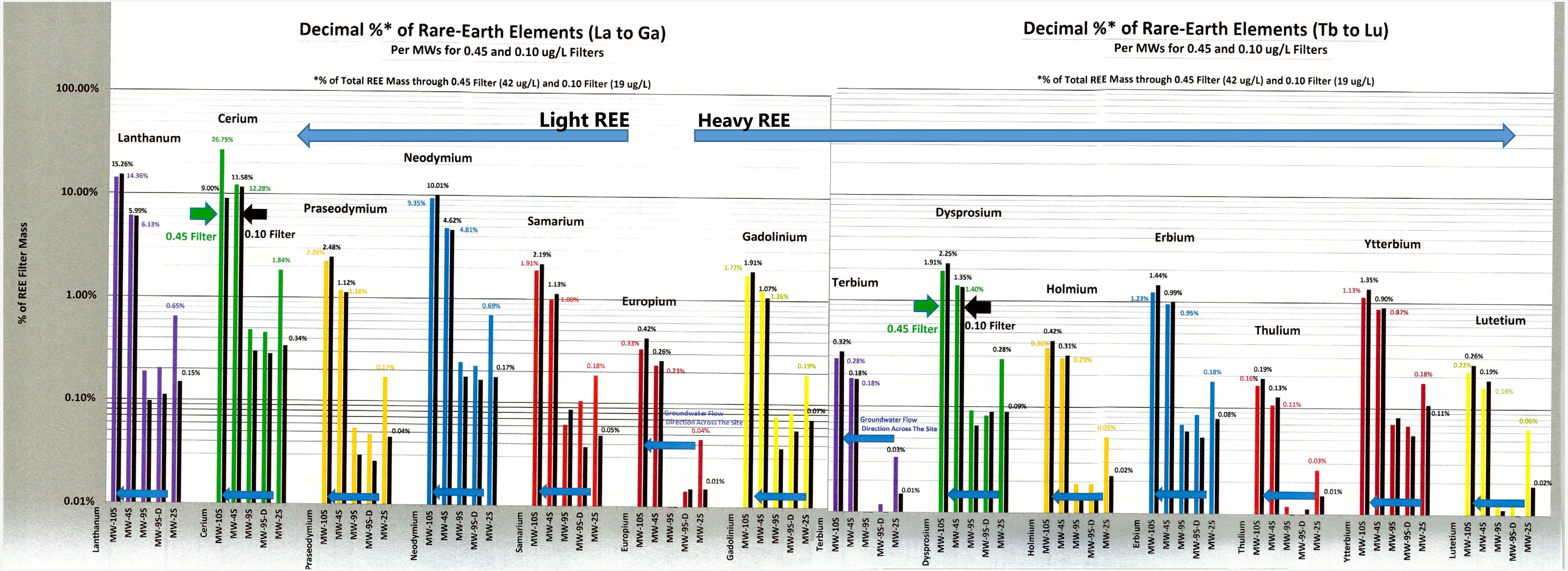
❖ Research conducted on eastern and western coal, and Gulf Coast lignite (history)

REE in Shallow Groundwater in U.S.



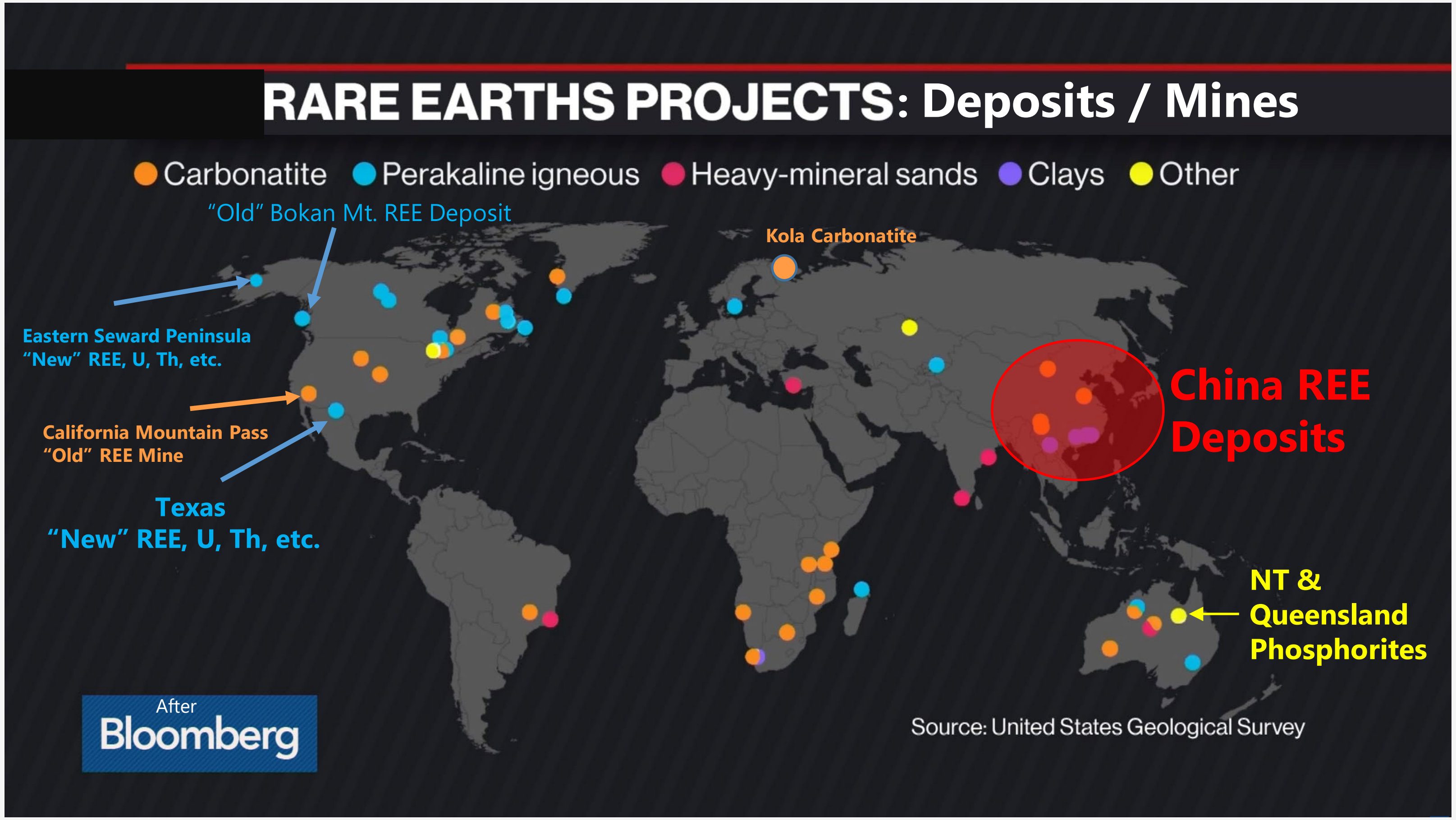
- Even in the colloidal-sized particles, **REE** content reflects similar pattern of **REE** distribution.
- Shallow groundwater samples from 2 separate monitoring well locations containing high **arsenic** content (1,000 ppm) passing through 0.45 ug and 0.10 ug filters show **REE** distribution only 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)

REE Projects Known or Under Evaluations/Development



Simandl & Paradis (2018)

- **Types of REE Deposits**

- Example Carbonatites:

Mountain Pass Carbonatite (US) (Haxel (2005) associated with saturated to oversaturated (in SiO_2), 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.

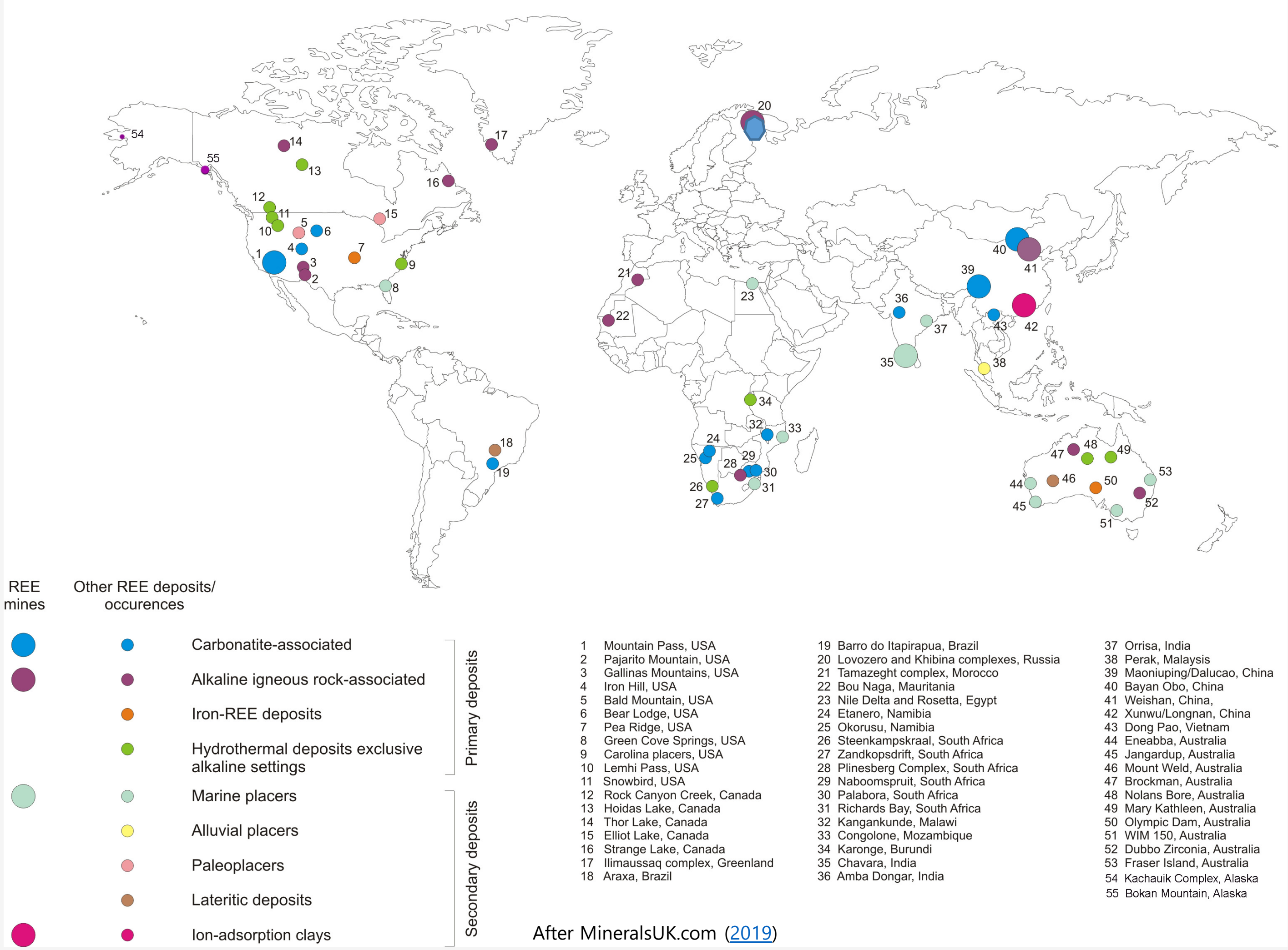
Kola Carbonatite (Russia) (Zaitsev, et al., (2014): burbankite, carbocernaite, hydrous ancylite, Ca- and Ba fluocarbonatessynchysite, bastnäsite and cordylite; in addition to oxides (loparite), silicates (cerite), and phosphates (monazite), etc.

- 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.

World REE Deposits and Mines

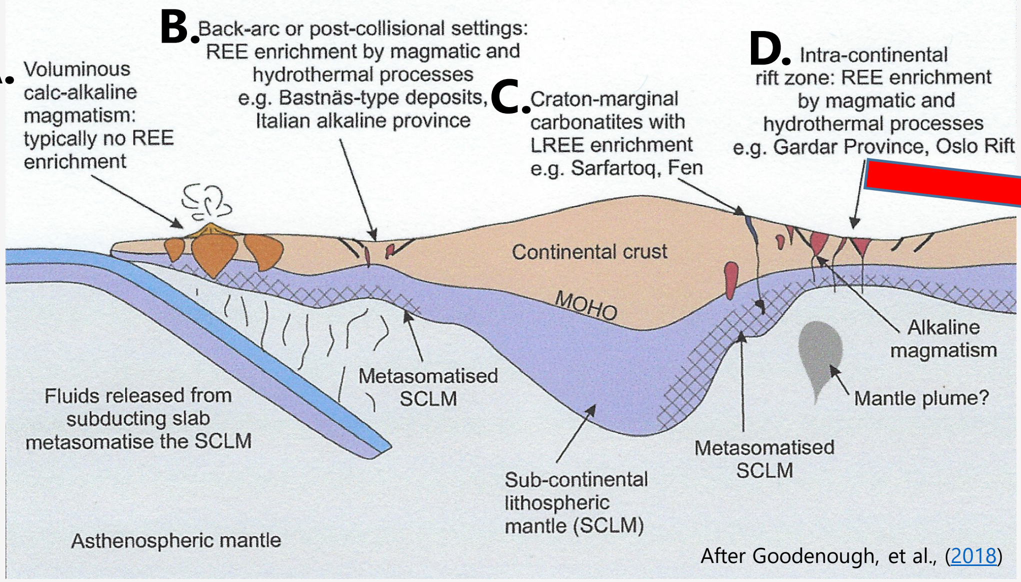


After MineralsUK.com (2019)

- 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.

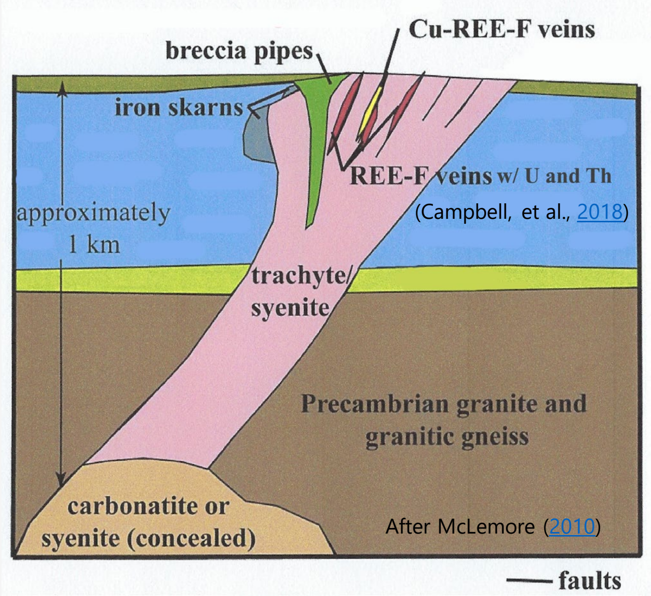
Typical REE Mineralization Produced in Igneous and Volcanic Environments

Type A.



After Goodenough, et al., (2018)

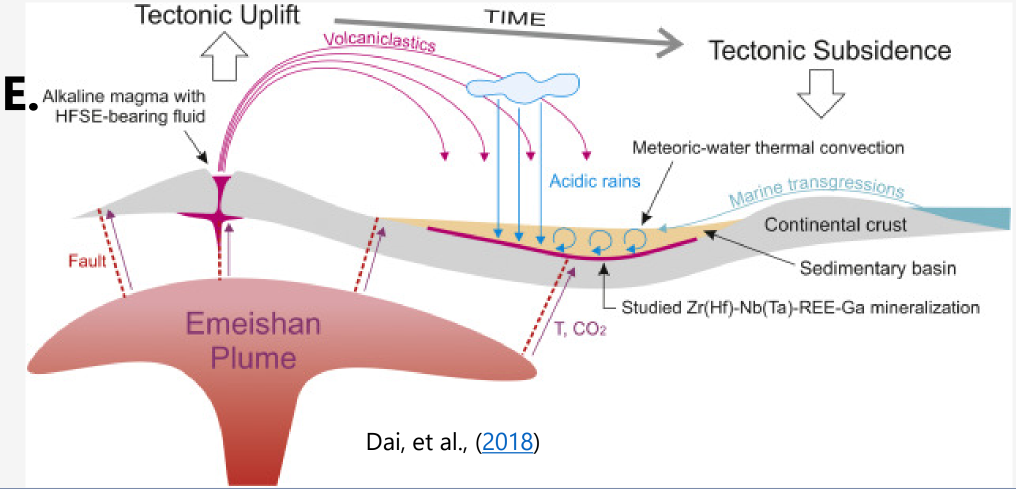
D.



(Campbell, et al., 2018)

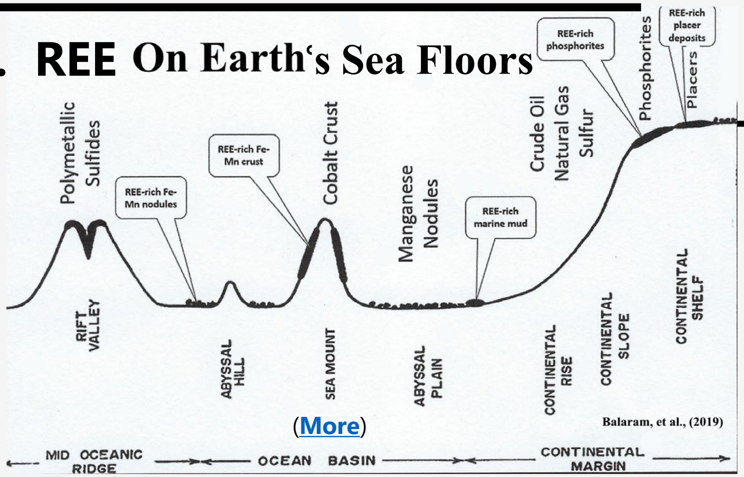
After McLemore (2010)

Type E.



Dai, et al., (2018)

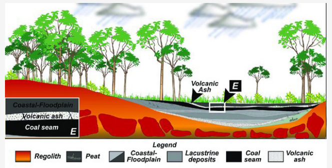
Type F. REE On Earth's Sea Floors



(More)

Sea-Floor REE accumulations from volcanism and from space dust (?)

G. REE in Coal



Swamps, lagoons, and wherever coals & lignite accumulated.
Enlarge

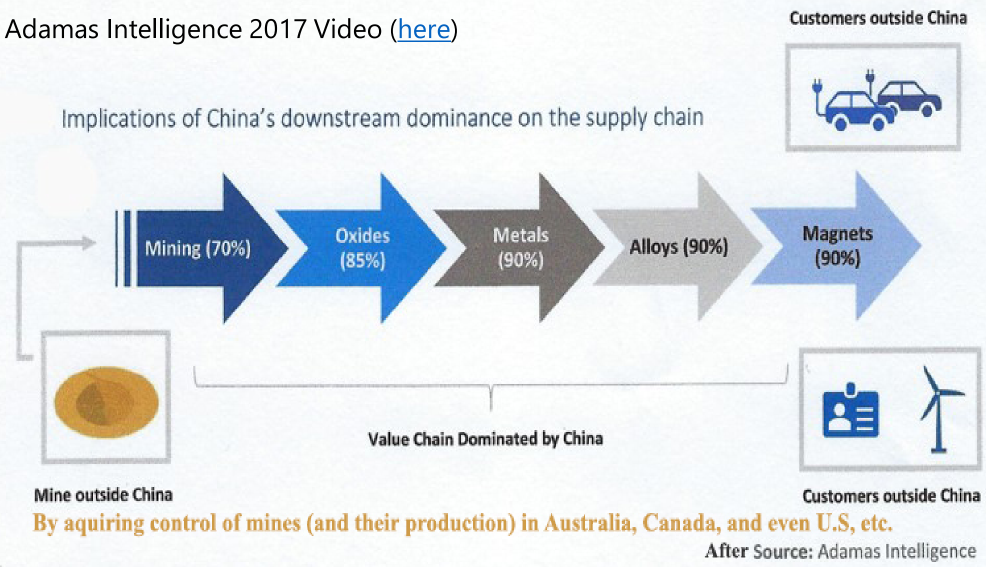
Ramkumar, et al. (2017)

The Major Sources of REE: Bayan Obo, Weishan & Vicinity

Bayan Obo Rare Earth Mines, Inner Mongolia, China

- **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.

Adamas Intelligence 2017 Video (here)



Older REE Deposits in North America

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

Name	Country	State/Province	REO (Mt)	REO %	Source	Comments
Carbonatite						
Iron Hill	USA	Colorado	2.600	0.42	Jackson and Christiansen (1993)	By-product of Nb
Mountain Pass	USA	California	1.800	8.9	Castor and Nason (2004)	5% REO cut-off
Bear Lodge	USA	Wyoming	0.380	3.3	Meyer (2002)	Carbonatite dikes
Oka	Canada	Quebec	0.221	0.1	Orris and Grauch (2002)	By-product of Nb
Wet Mountains	USA	Colorado	0.140	1.0	Orris and Grauch (2002)	Dike deposits, high Th
Hicks Dome	USA	Illinois	0.062	0.42	Jackson and Christiansen (1993)	By-product of Nb
Alkaline rock						
Thor Lake	Canada	NW Territories	1.547	0.41	Orris and Grauch (2002)	
Strange Lake	Canada	Labrador–Quebec	0.440	0.85	Richardson and Birkett (1996)	
Lackner Lake	Canada	Ontario	0.130	2.72	Orris and Grauch (2002)	
Pajarito Mountain	USA	New Mexico	0.004	0.18	Jackson and Christiansen (1993)	REO = Y_2O_3 only
Kipawa Lake	Canada	Quebec	ND	≥0.10	Richardson and Birkett (1996)	REO = Y_2O_3 only
Iron oxide-REE						
Mineville	USA	New York	0.160	1.04	Jackson and Christiansen (1993)	Apatite in mill tails
Pea Ridge	USA	Missouri	0.072	12.0	Orris and Grauch (2002)	
Vein						
Powderhorn	USA	Colorado	0.886	0.36	Jackson and Christiansen (1993)	Stockwork veins
Lemhi Pass	USA	Idaho	0.199	0.51	Jackson and Christiansen (1993)	
Hoidas Lake	Canada	Saskatchewan	0.035	2.56	Great Western Minerals Group (2007)	Allanite and apatite
Diamond Creek	USA	Idaho	0.003	1.22	Jackson and Christiansen (1993)	
Placer						
Oak Grove	USA	Tennessee	0.157	0.09	Jackson and Christiansen (1993)	Monazite
Idaho placers	USA	Idaho	0.150	0.01	Jackson and Christiansen (1993)	Mostly monazite
Hilton Head Island	USA	South Carolina	0.061	0.01	Jackson and Christiansen (1993)	Monazite
Carolina placers	USA	N. and S. Carolina	0.057	ND	Jackson and Christiansen (1993)	Monazite
Cumberland Island	USA	Georgia	0.027	0.01	Jackson and Christiansen (1993)	Monazite
Green Cove Spring	USA	Florida	0.005	0.005	Jackson and Christiansen (1993)	Monazite
Paleoplacer						
Elliott Lake	Canada	Ontario	0.020	0.009	Jackson and Christiansen (1993)	Monazite
Bald Mountain	USA	Wyoming	0.014	0.12	Jackson and Christiansen (1993)	Monazite
Phosphorite						
Idaho deposits	USA	Idaho	0.100	0.1	Jackson and Christiansen (1993)	Several deposits
Fluorite						
Gallinas Mountains	USA	New Mexico	0.001	2.95	Orris and Grauch (2002)	

ND, no data; REE, rare earth element; REO, rare earth oxide. Caster (2007)

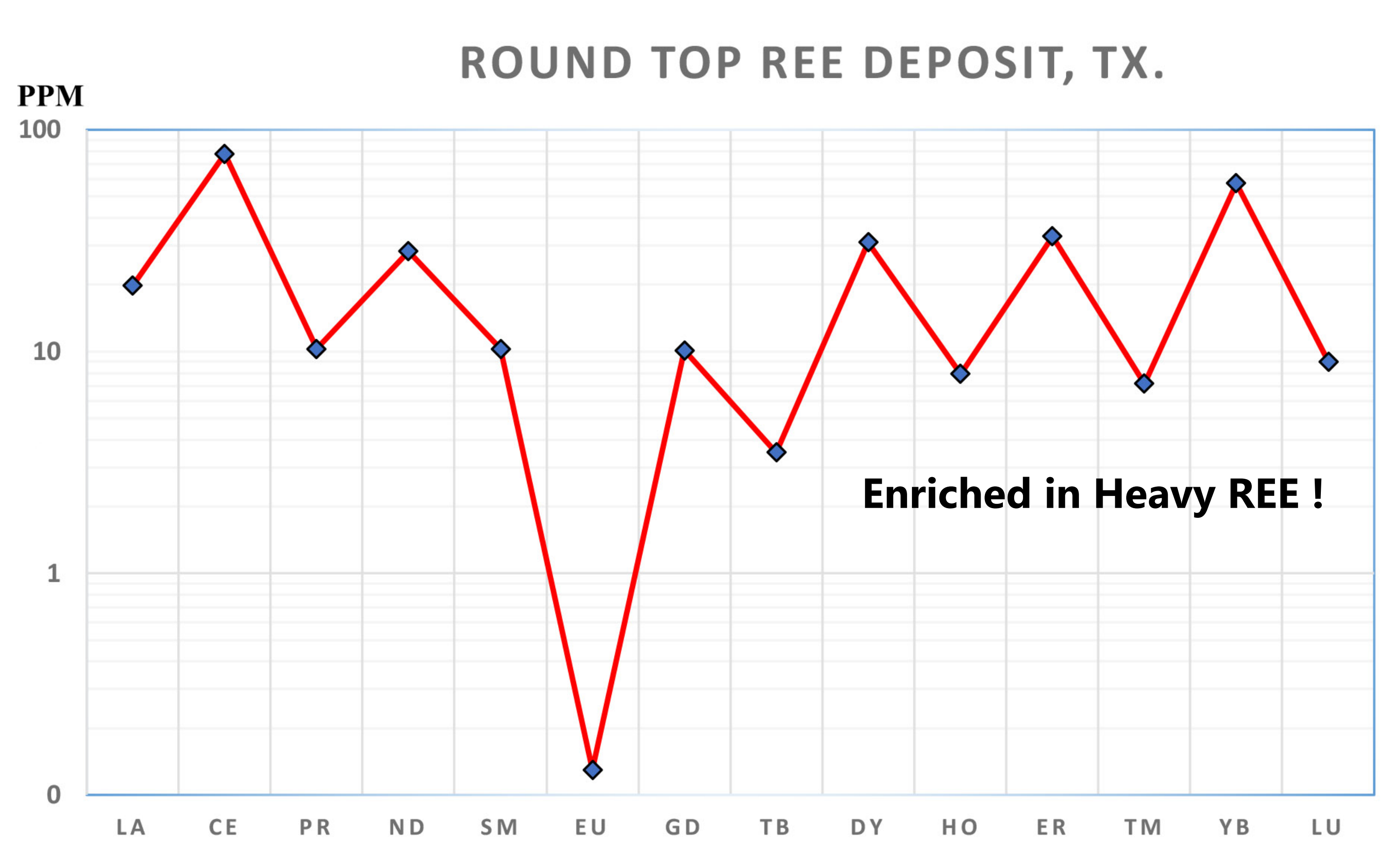
REO analyses of North American REE concentrates and ores (normalized to approx. 100 wt% REO + Y_2O_3)

Oxide	Bear Lodge bulk ore	Mountain Pass bastnasite	Green Cove Spring monazite	Mineville apatite	Thor Lake xenotime	Strange Lake bulk ore
La	30.37	33.79	17.5	15.75	0.1	4.58
Ce	45.50	49.59	43.7	31.12	0.02	11.95
Pr	4.65	4.12	5.0	3.62	0.1	1.36
Nd	15.82	11.16	17.5	15.46	0.2	4.26
Sm	1.83	0.85	4.9	2.94	1.8	2.07
Eu	0.35	0.105	0.16	0.39	0.7	0.15
Gd	0.74	0.21	6.6	3.52	11.6	2.45
Tb	0.05	0.016	0.26	1.86	2.5	0.33
Dy	0.16	0.034	0.9	1.86	15.6	8.24
Ho	0.02	0.004	0.11	0.59	3.1	1.70
Er	0.03	0.006	TR	1.66	5.41	4.90
Tm	<0.01	0.002	TR	0.49	0.6	0.69
Yb	0.49	0.002	0.21	1.66	2.2	4.02
Lu	<0.01	ND	TR	0.59	0.7	0.42
Y	<0.01	0.13	3.2	18.49	55.31	52.78
Total	100.01	100.00	100.04	100.00	99.94	99.90

Data sources: Bear Lodge, Rare Element Resources (2005); Mountain Pass, Castor (1986); Green Cove Spring, Hedrick (2003); Mineville, Roeder *et al.* (1987); Thor Lake, Avalon Ventures (2007); Strange Lake, J. W. Keim, unpubl. data (1983). ND, no data; REE, rare earth element; 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**.

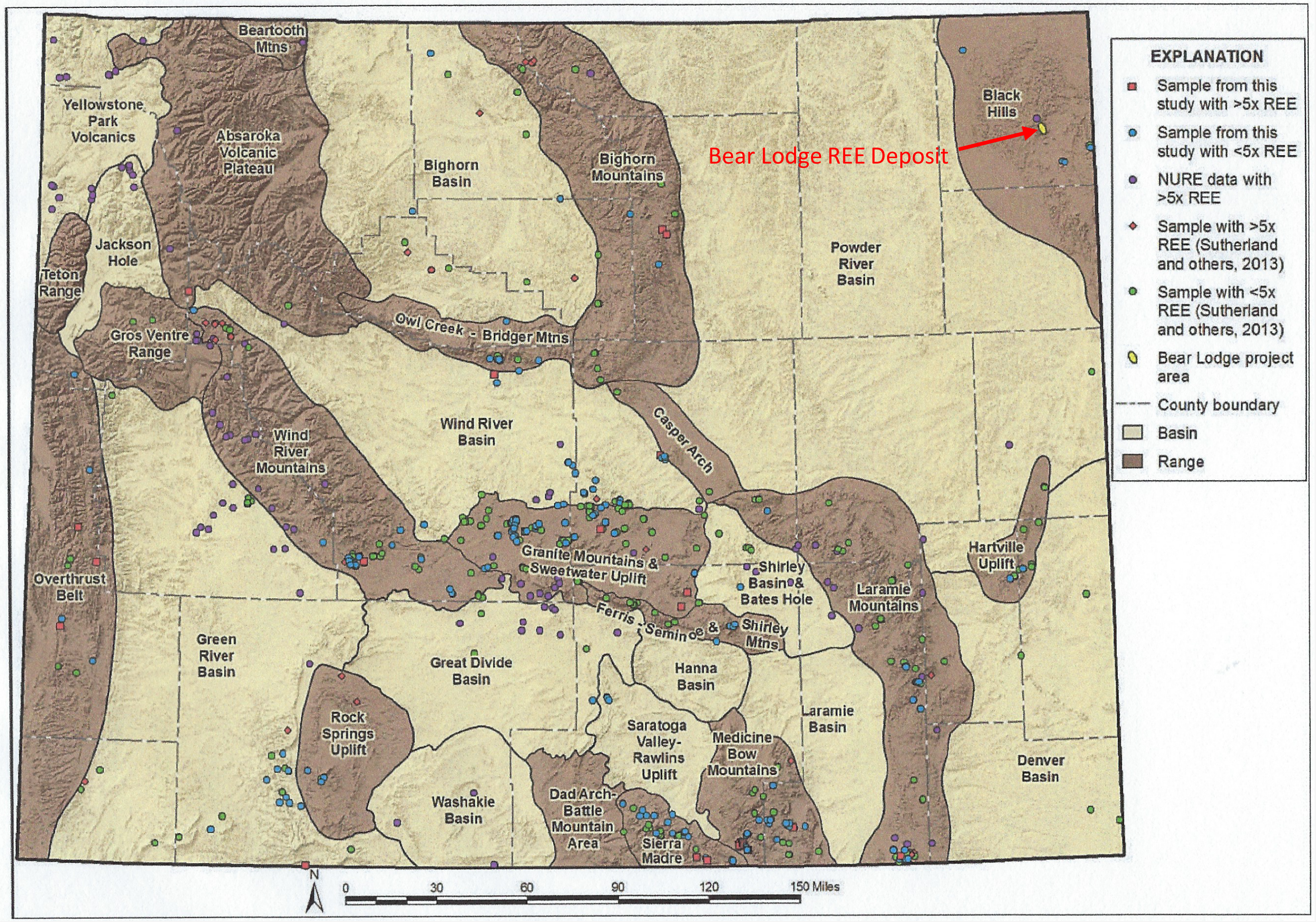
NEW U.S. REE and Other CMs in Texas



USA Rare Earth (2020) and Texas Mineral Resources Corp. (2019)

- 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**

REEE Exploration in Wyoming

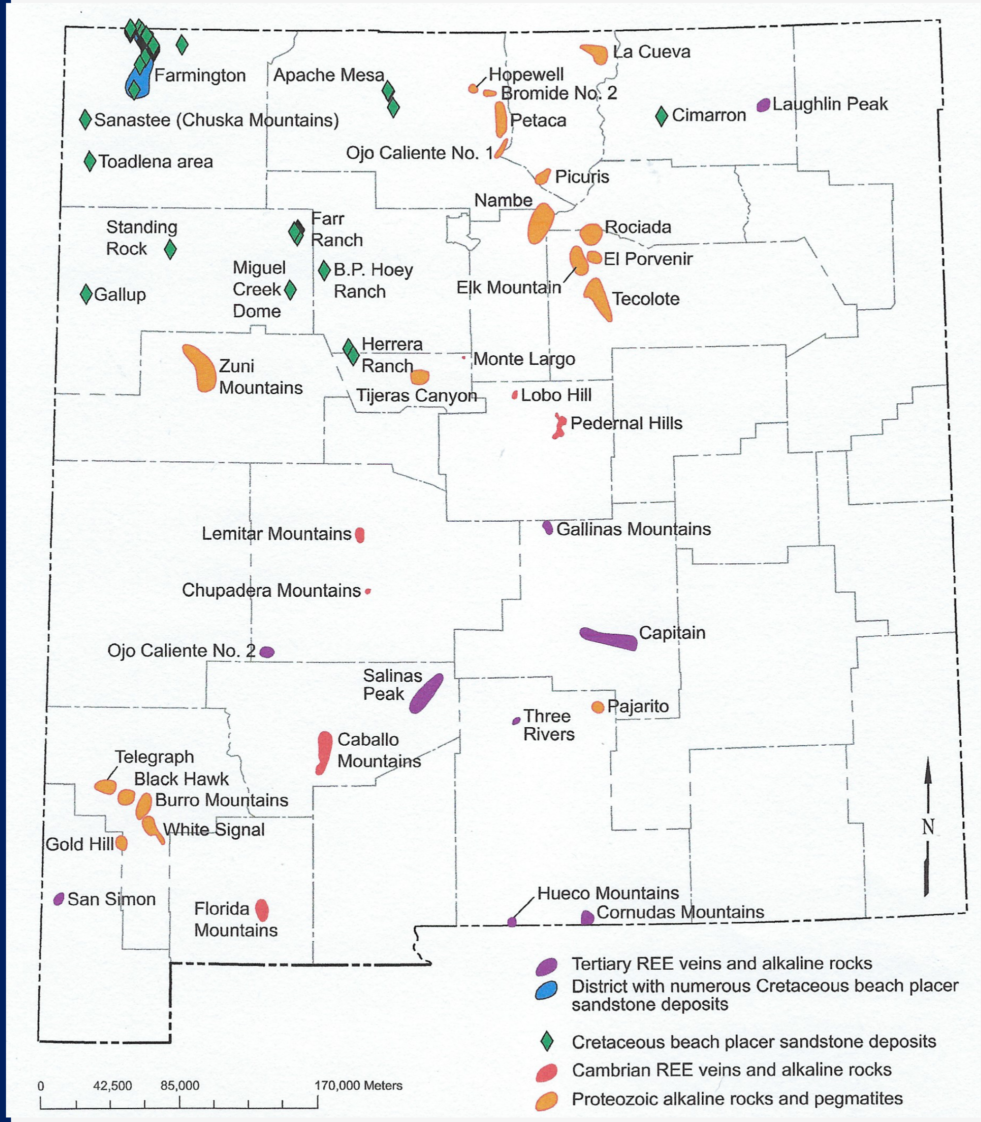


- Wyoming Under Explored **REE** (Sutherlund, et al., (2013)), (Sutherland & Cola (2016))

- 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 (**F**e, **M**n, **R**EE) - 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

REE Exploration in New Mexico



- 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
  5. K-T Boundary (Andersen, et al., 2015)

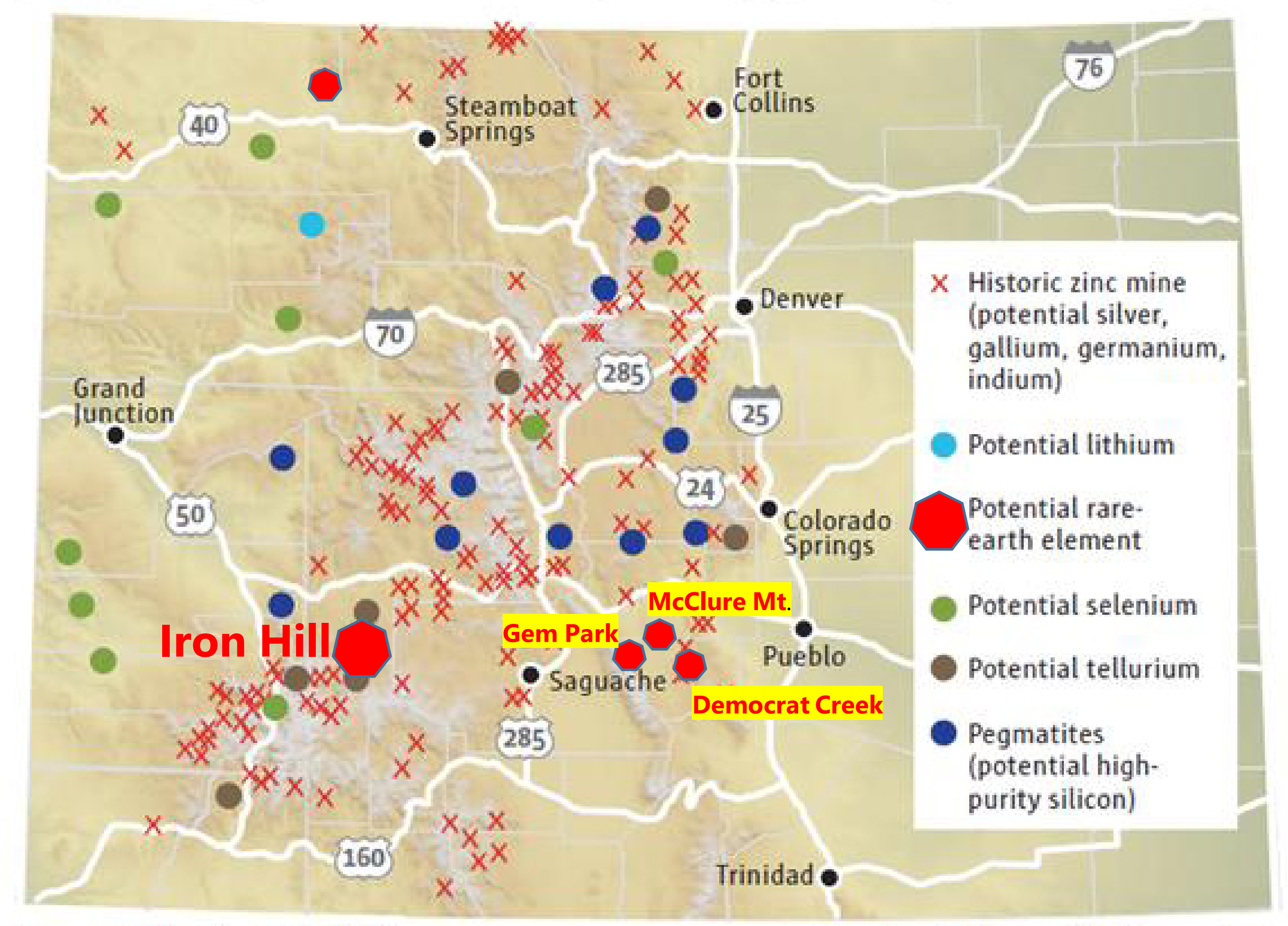
- The most significant deposits in the state are found in veins and breccias although some pegmatites contain **REEs** (McLemore, et al., (1988)).

- 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)).

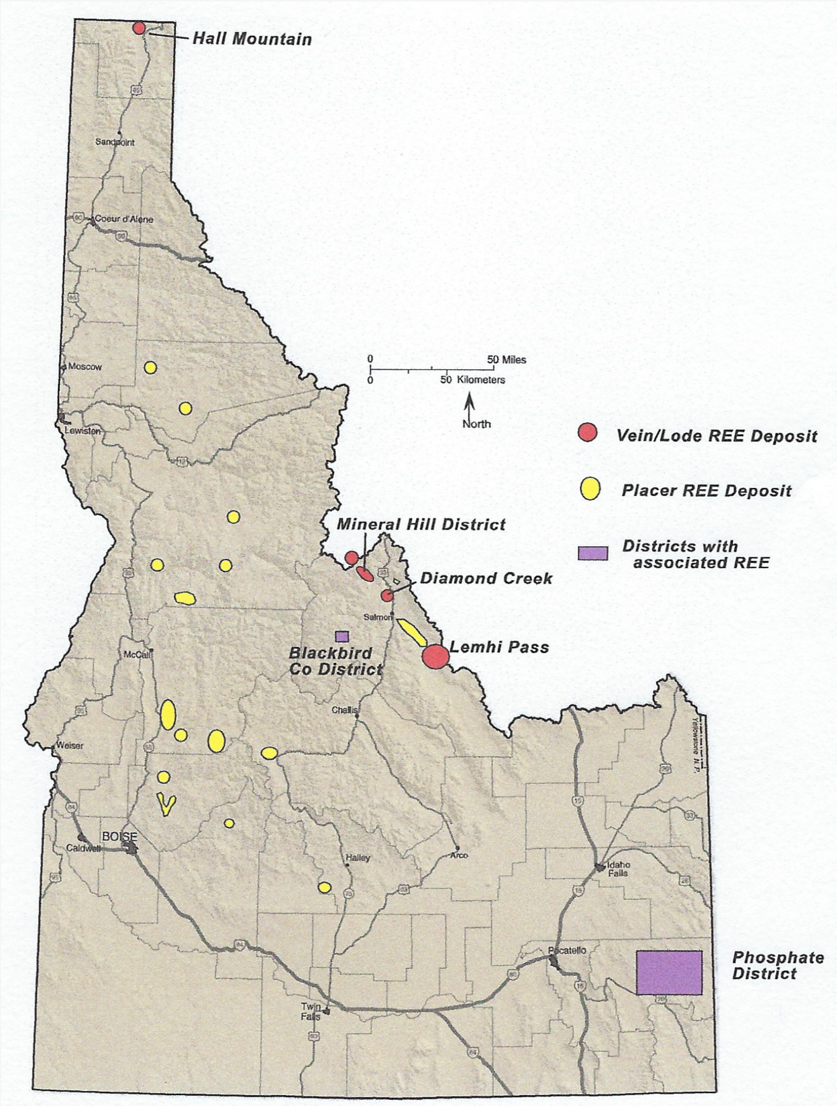
REEE Exploration in Colorado



Source: Colorado Geological Survey
Jonathan Moreno, The Denver Post

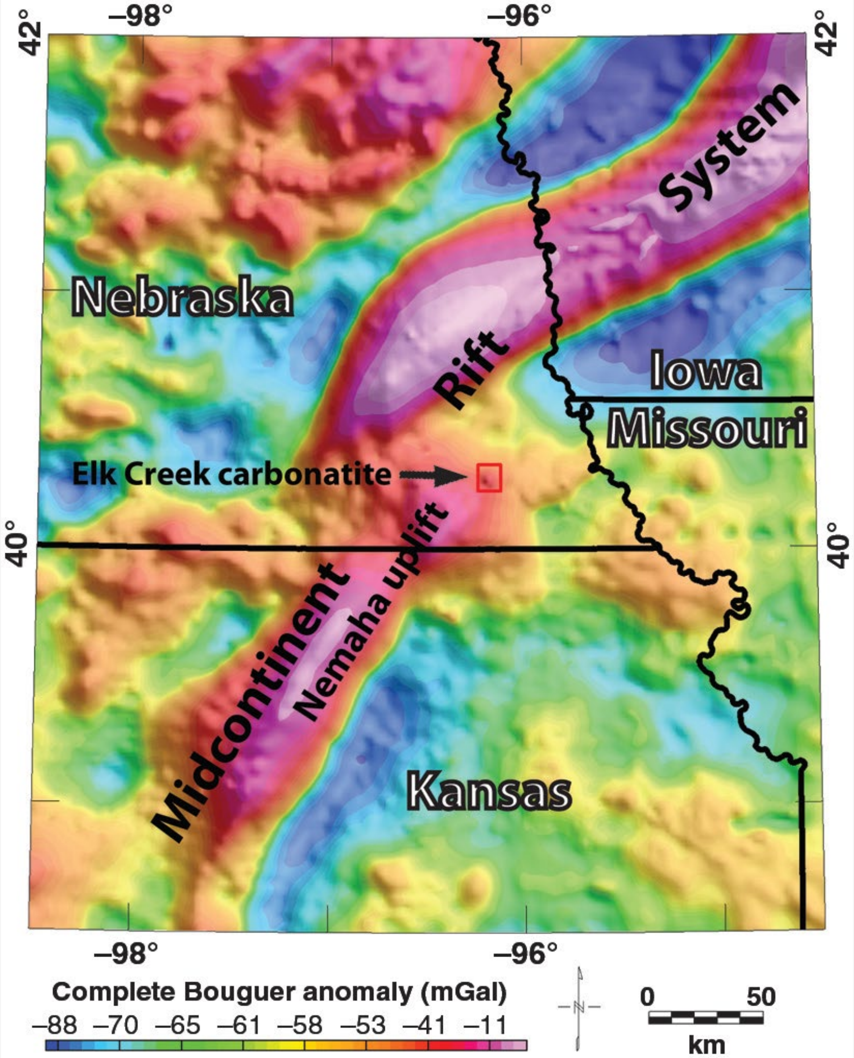
- U.S. Geological Survey has identified two locations for **REE** deposits:
- The Iron Hill Carbonatite Complex near the town of Powderhorn, about 22 miles southwest of Gunnison (Van Gosen (2009)),
- Geochemical Survey in the Iron Hill area (more) in Fremont and Custer counties
- Reported **REE** prospect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

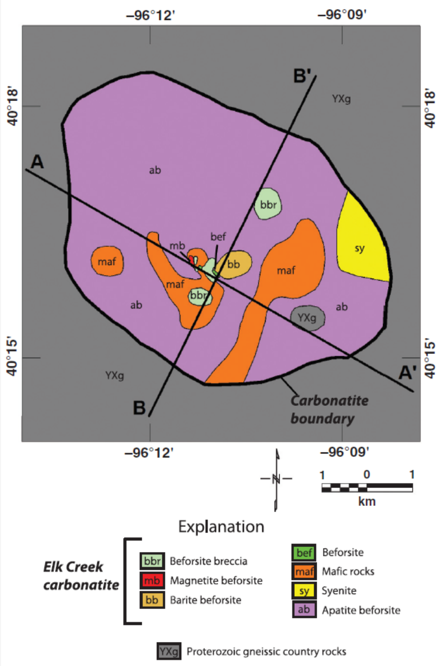
REE Exploration in Idaho



- 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

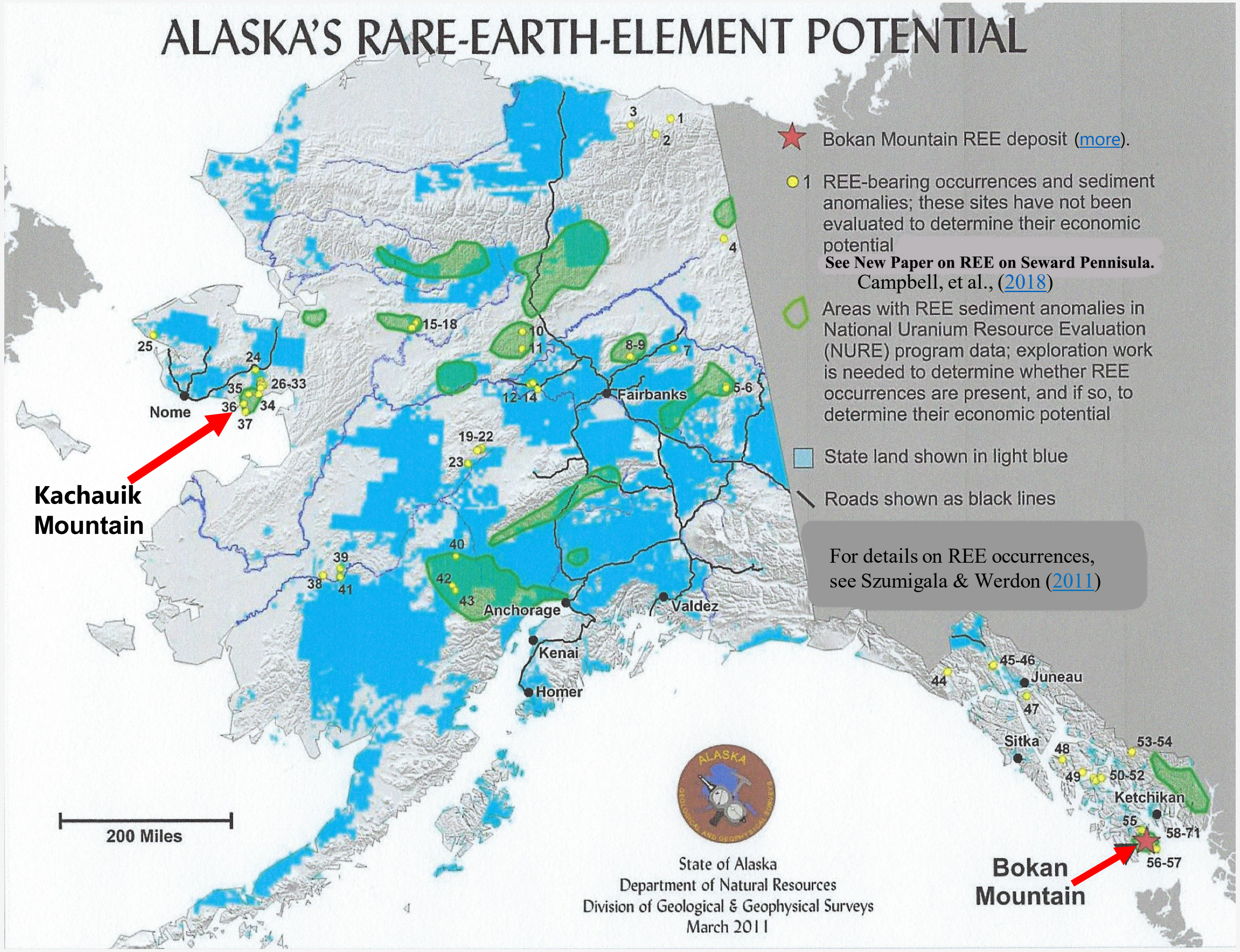




Elk Creek Carbonatite

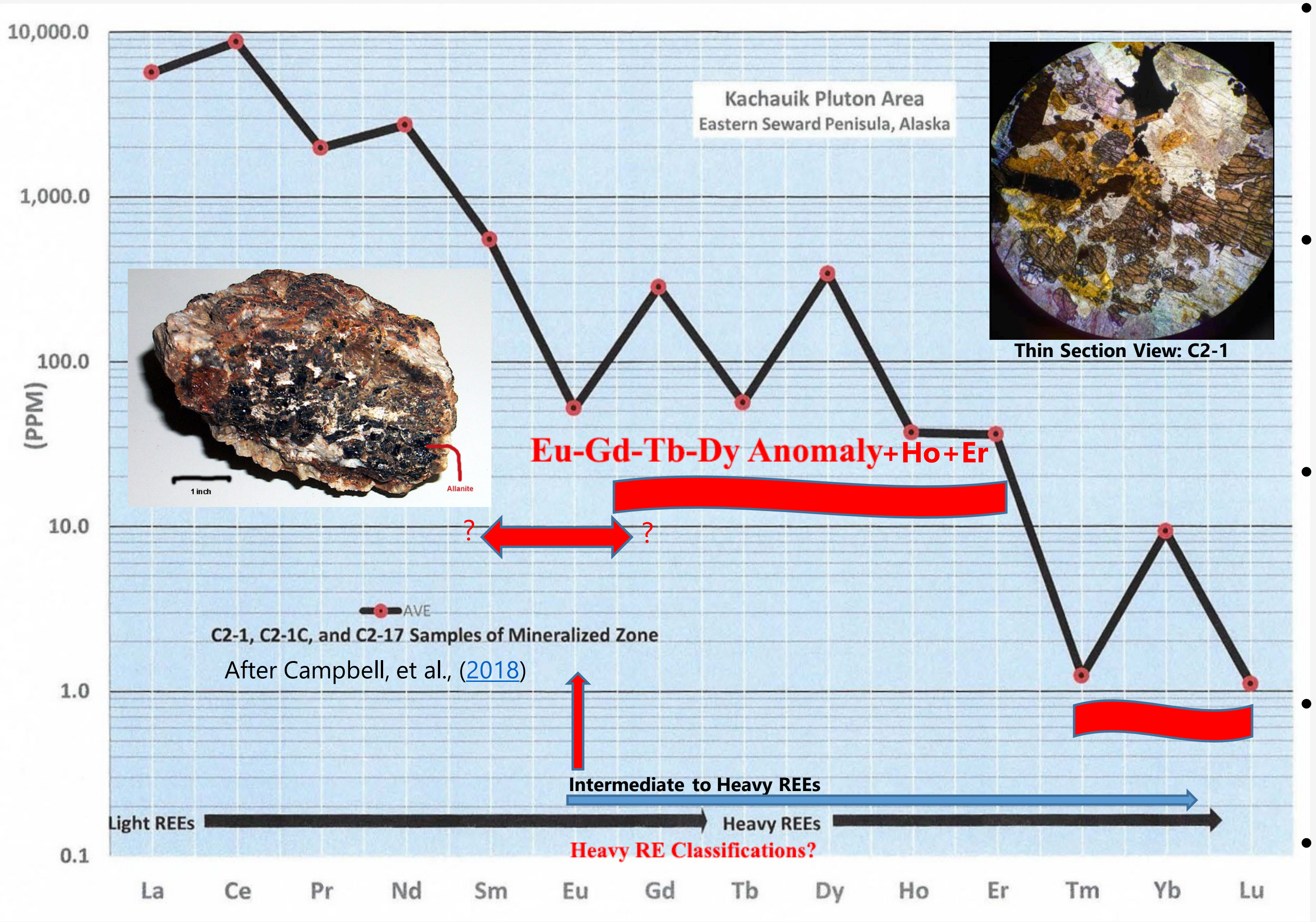
- Discovered 1970 – Framework Geophysical Program Gravity and Magnetic Anomalies – 8 mgal and 800 gammas respectively,
- Cylindrical mass of infinite depth and radius of 5,500 ft. [1,676 m]. Coring 1971 – At 630 ft. – iron-rich silicate bearing carbonate rock,
- Dolomite and ankerite with lesser amount 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** .... 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



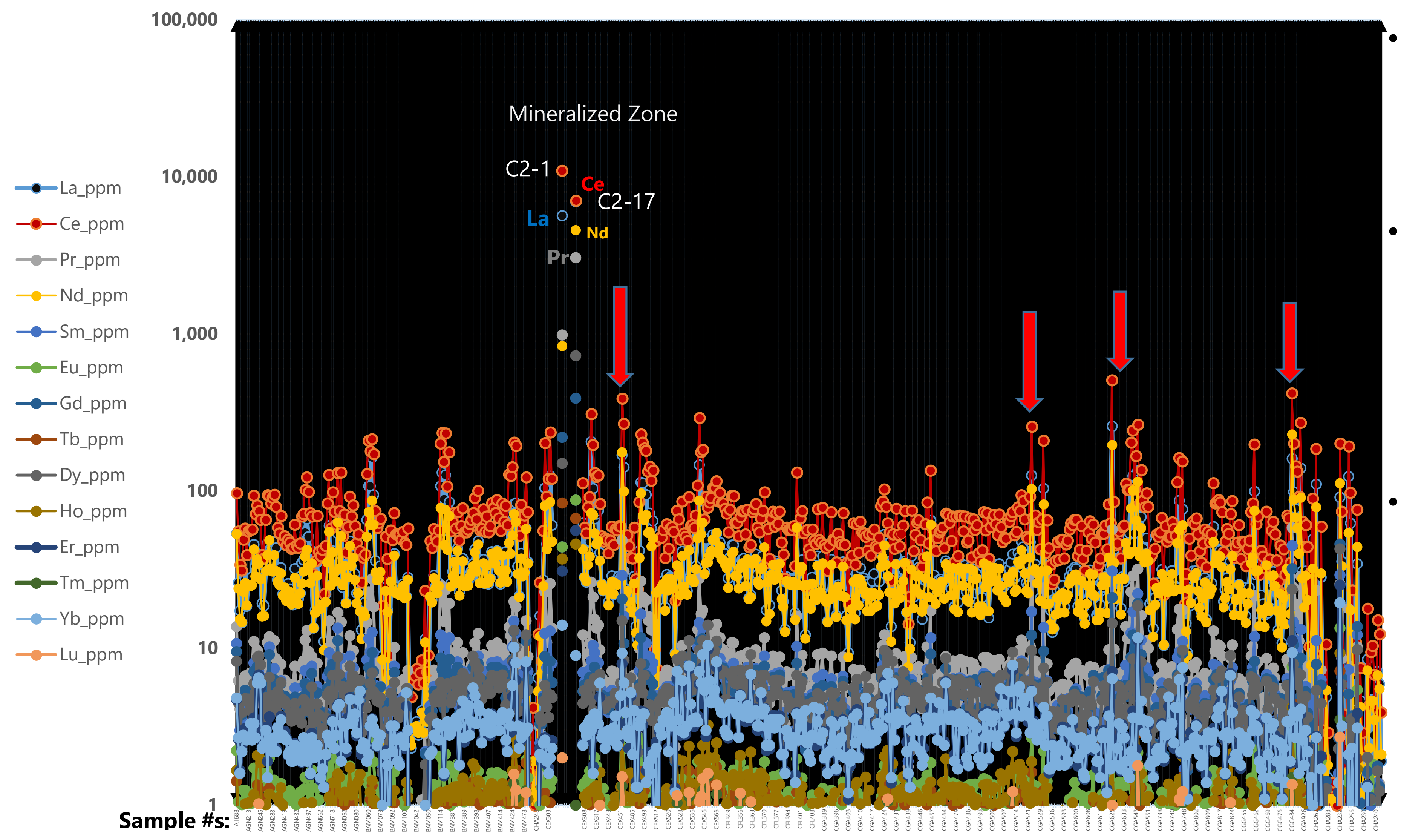
- Bokan Mountain **REE**, **U**, **Th** occurrences are well known. UCORE is developing as economics permit.
  - Mineral resource of 4.84 million tonnes (5.33 million tons) grading 0.601% total rare earth oxides (**TREO**), and Inferred Mineral Resource of 1.04 million tonnes (1.14 million tons) grading 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).

REE Redistribution in Mineralized Zones in Seward Peninsula, Alaska



- 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.

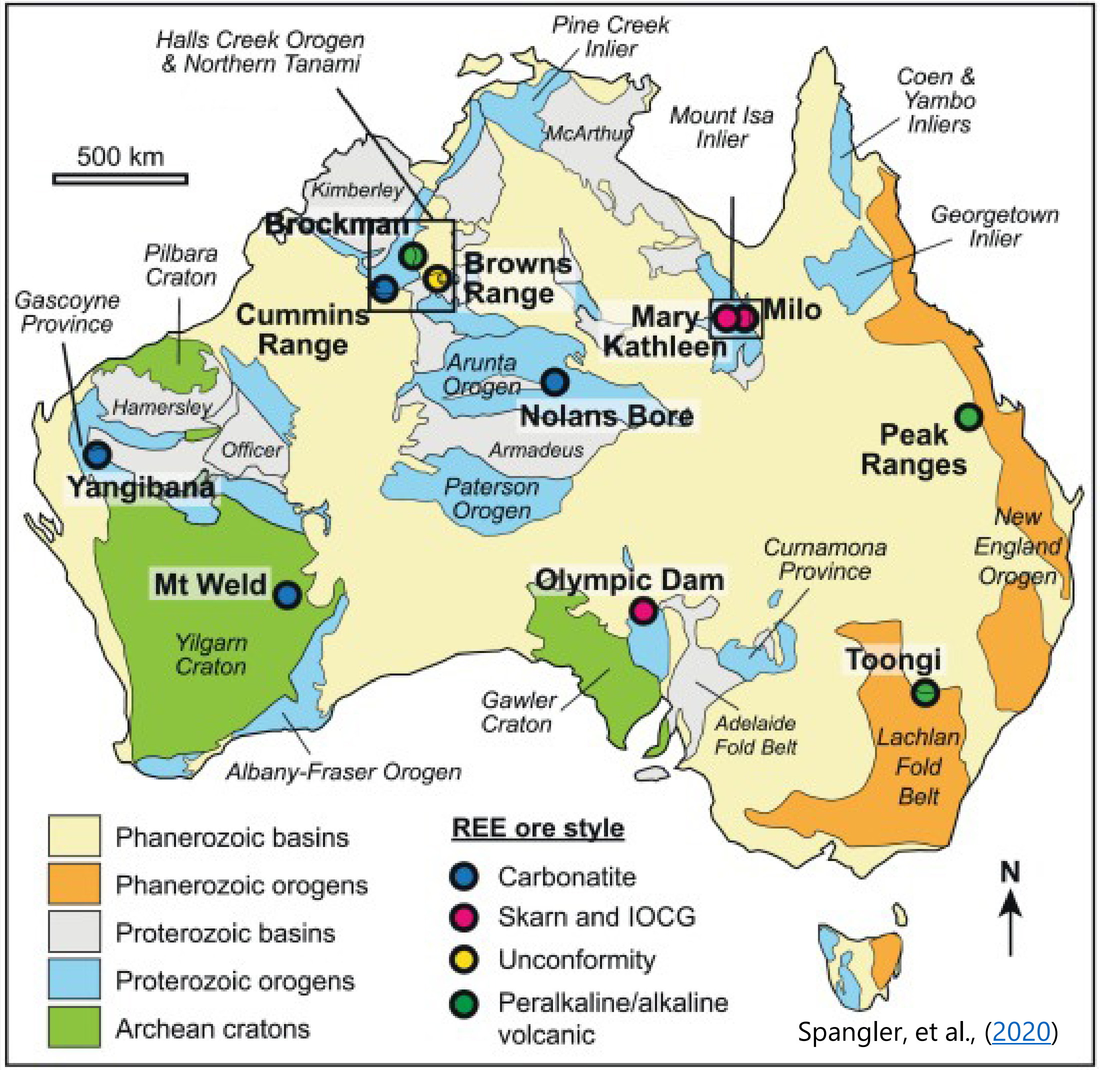
REEE in Sediment of Surrounding Areas, Seward Peninsula, Alaska



- 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.

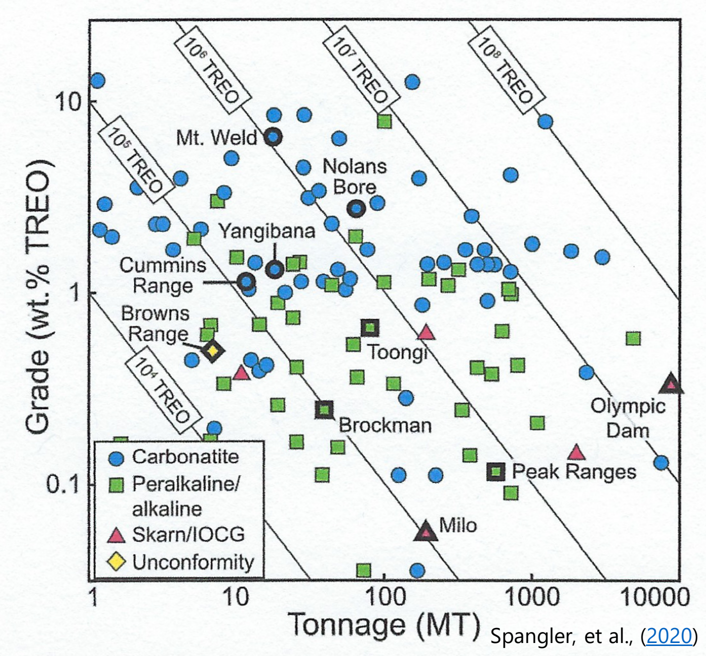
(Campbell, et al., , (2018)

Australia REE Mines and Deposits



Spangler, et al., (2020)

- 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).

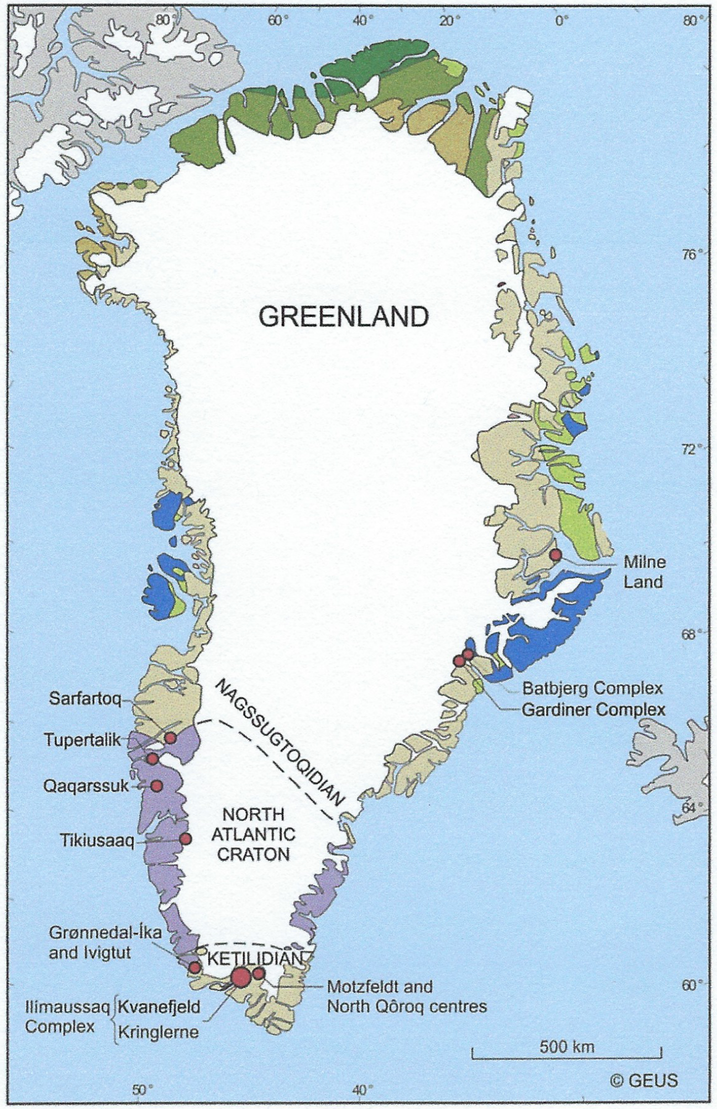


Spangler, et al., (2020)

- 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.

(Mudd, et al., (2018))

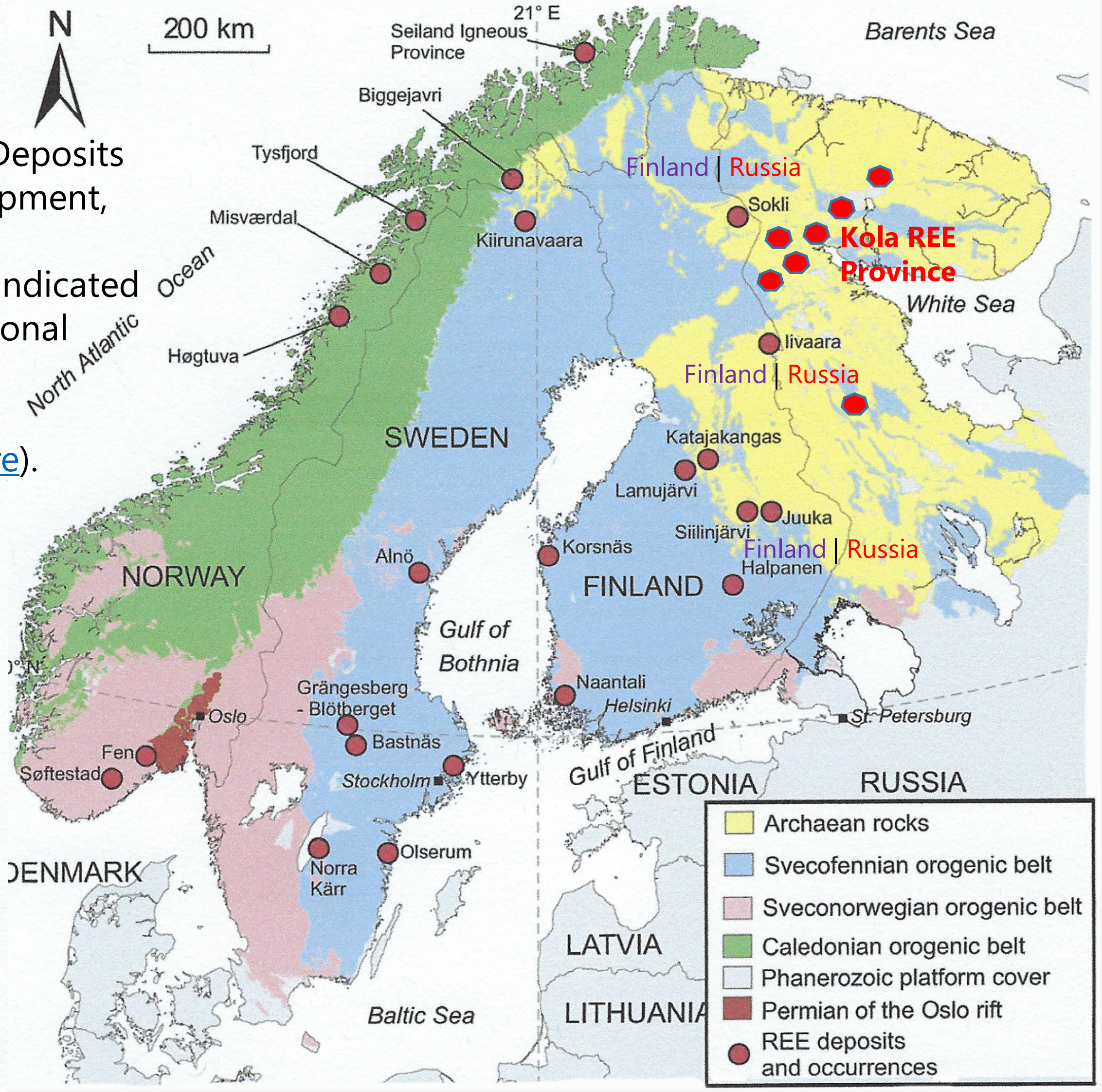
Greenland, Scandinavian & Russian REE Exploration and Deposits



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

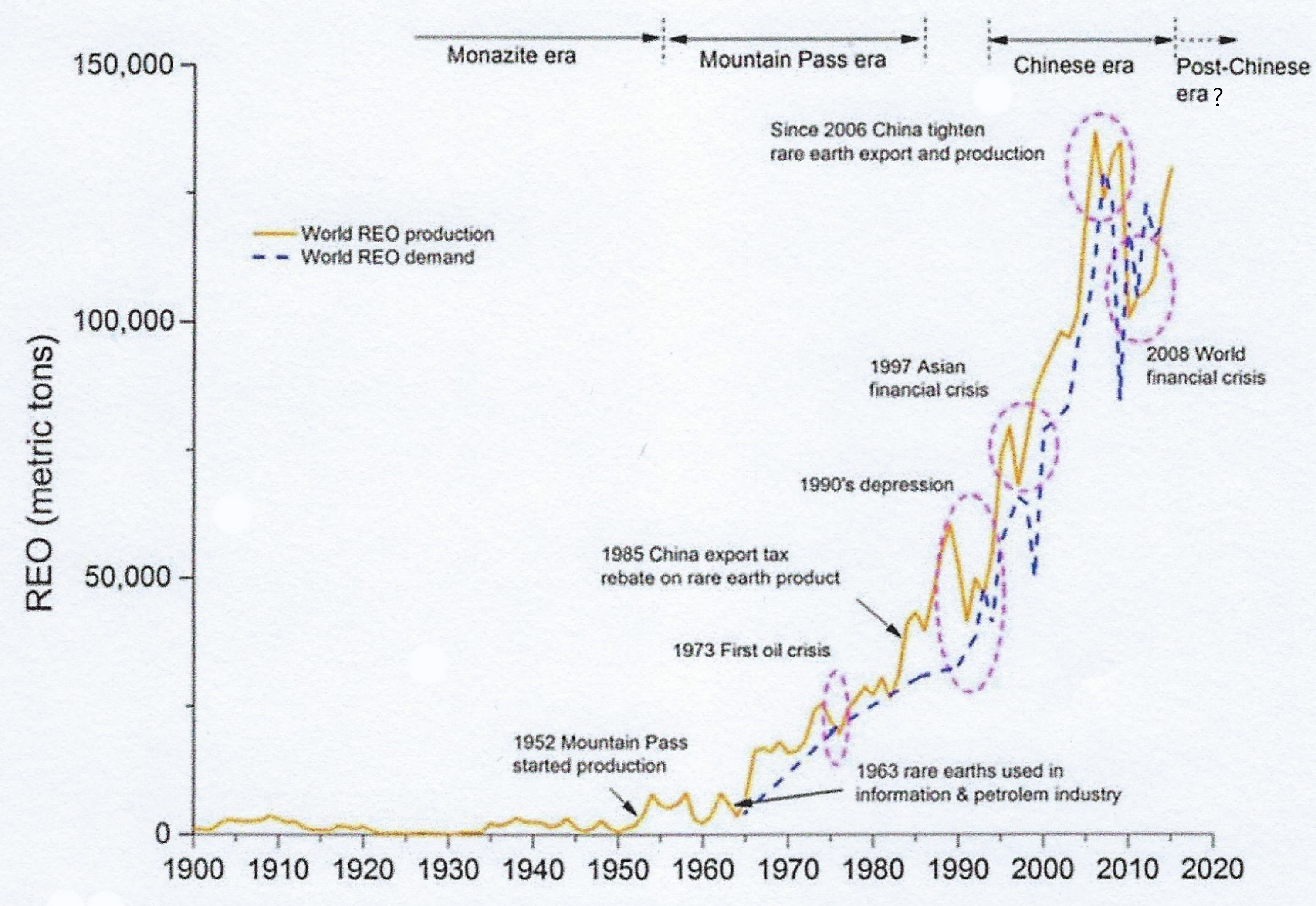
After Goodenough, et al., (2018)

- Cenozoic basalts
- Devonian - Palaeogene sedimentary rocks
- Cambrian - Silurian sedimentary rocks
- Proterozoic sedimentary rocks and volcanics
- North Greenland fold belt (Palaeozoic)
- Reworked Precambrian shield (1600-3100 Ma)
- Precambrian shield (2500-3900 Ma) 'North Atlantic Craton'
- REE deposits and occurrences



- 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



Summary of rare earth production and demand since 1900 (*From: Zhou, et al., 2017*)

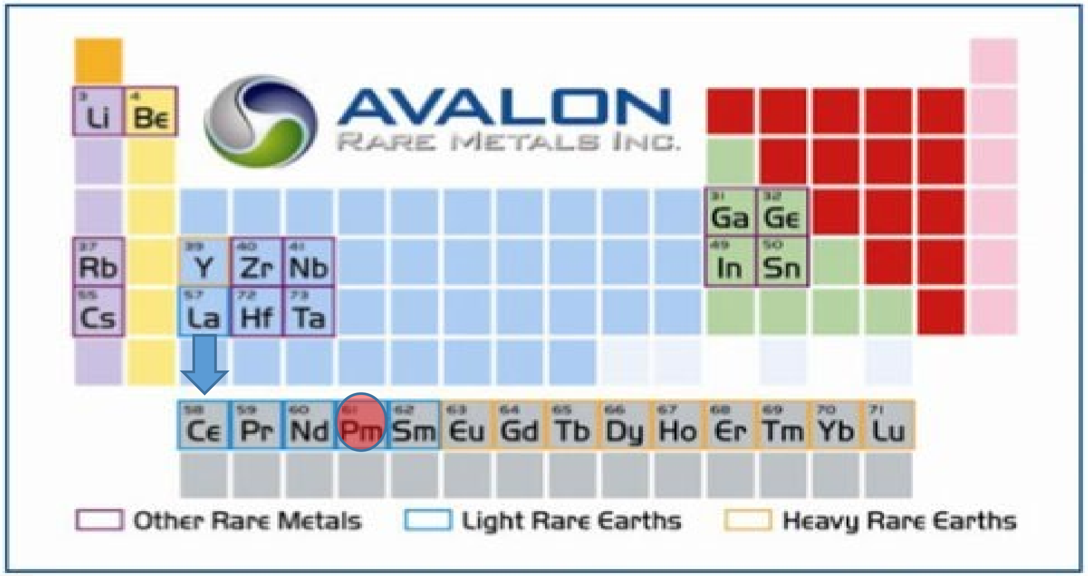
- **Technology Development:**
  - Geoscience Research,
  - Geoscience Discovery,
  - More Research, and
  - Industrial Applications
- **Industrial Development Stages:**
  - **REE** Exploration / G-T Evaluations,
  - Product Demand,
  - Resource Price,
  - Economic Pressure, and
  - Geopolitical Interaction
- **Employment Potential**
  - Academic Preparedness,
  - Jobs in U.S. (more),
  - Jobs in Australia (more),
  - Jobs in UK (more).

REEE Development vs. Price

- ❑ The 2011 price bubble stimulated many **REE** projects throughout the world, 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.

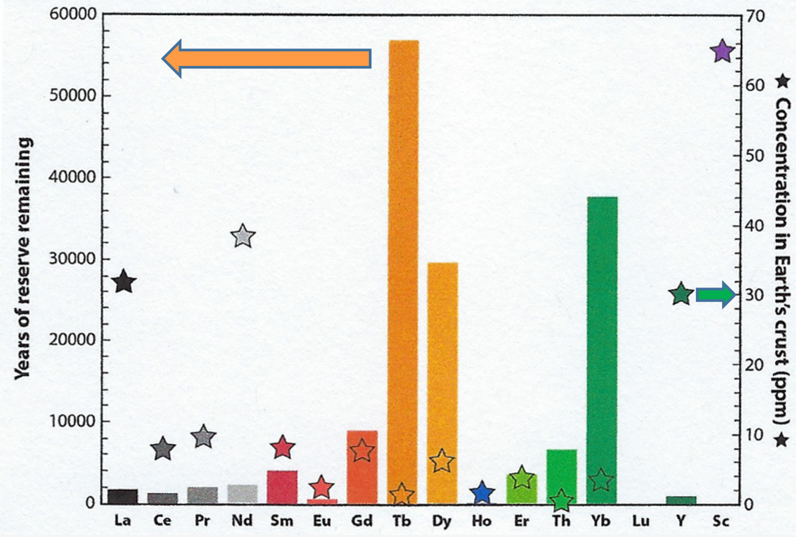
Industrial Use of REE and Critical Elements

Additional Elements Having Special Applications

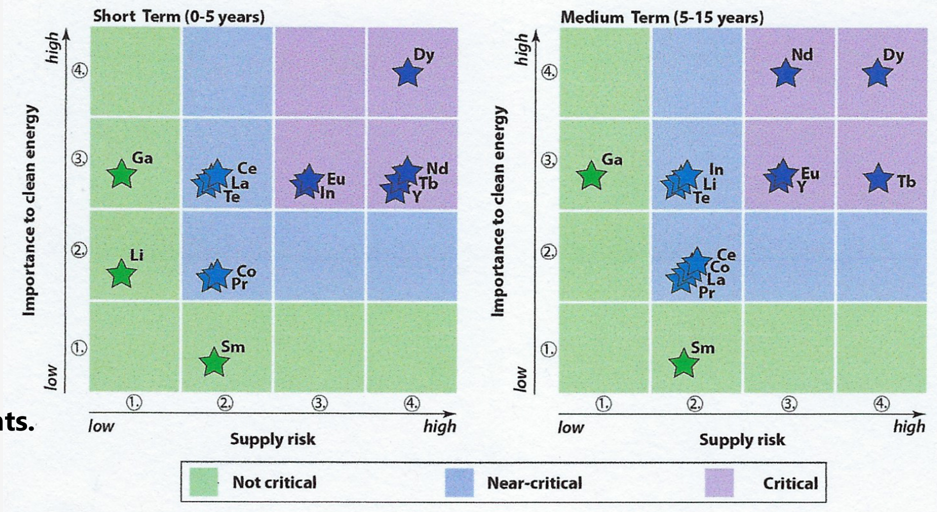


Light REE:
La = Lanthanum
Ce = Cerium
Pr = Praseodymium
Nd = Neodymium
Sm = Samarium

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

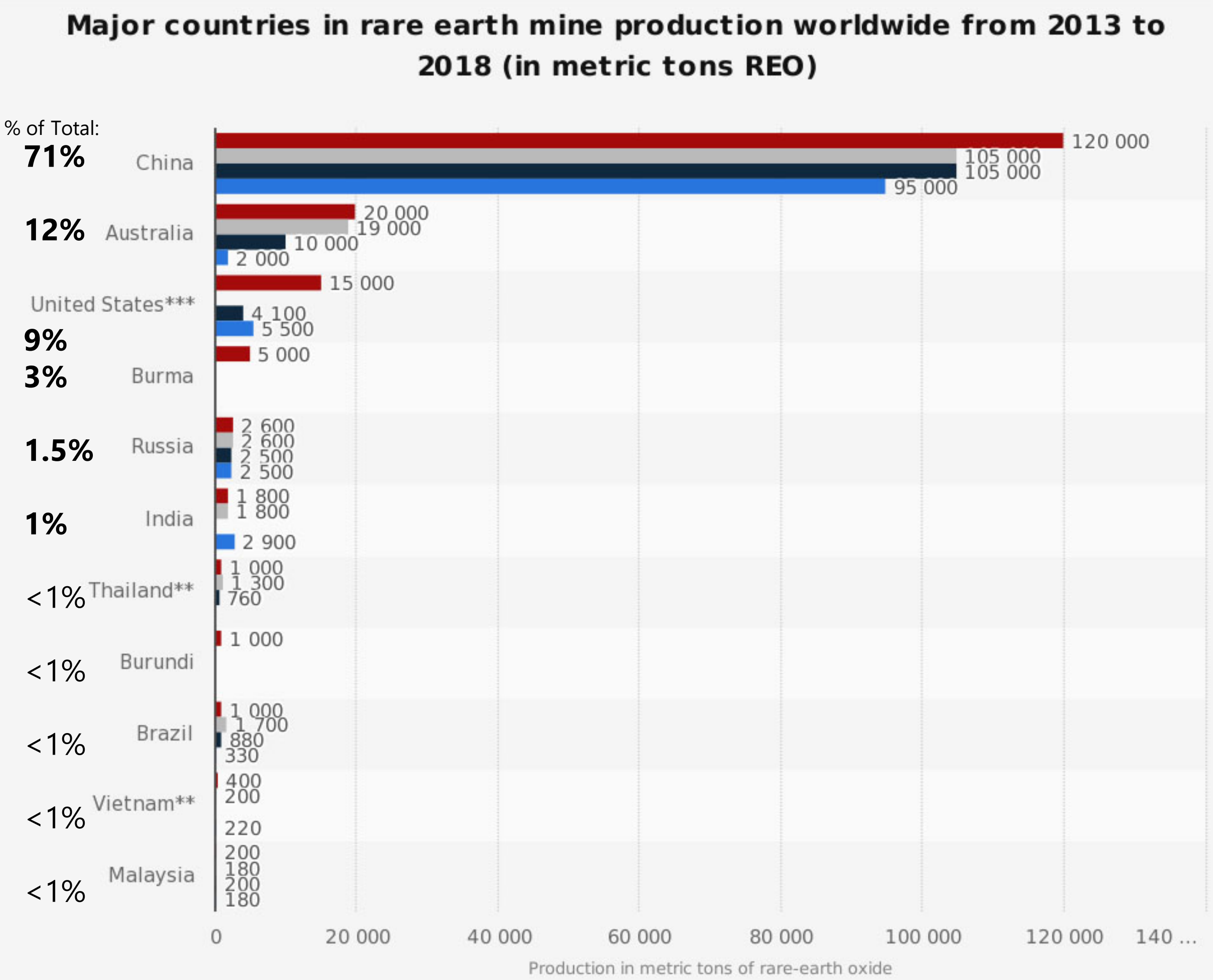


McLeod & Krekeler (2017)



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

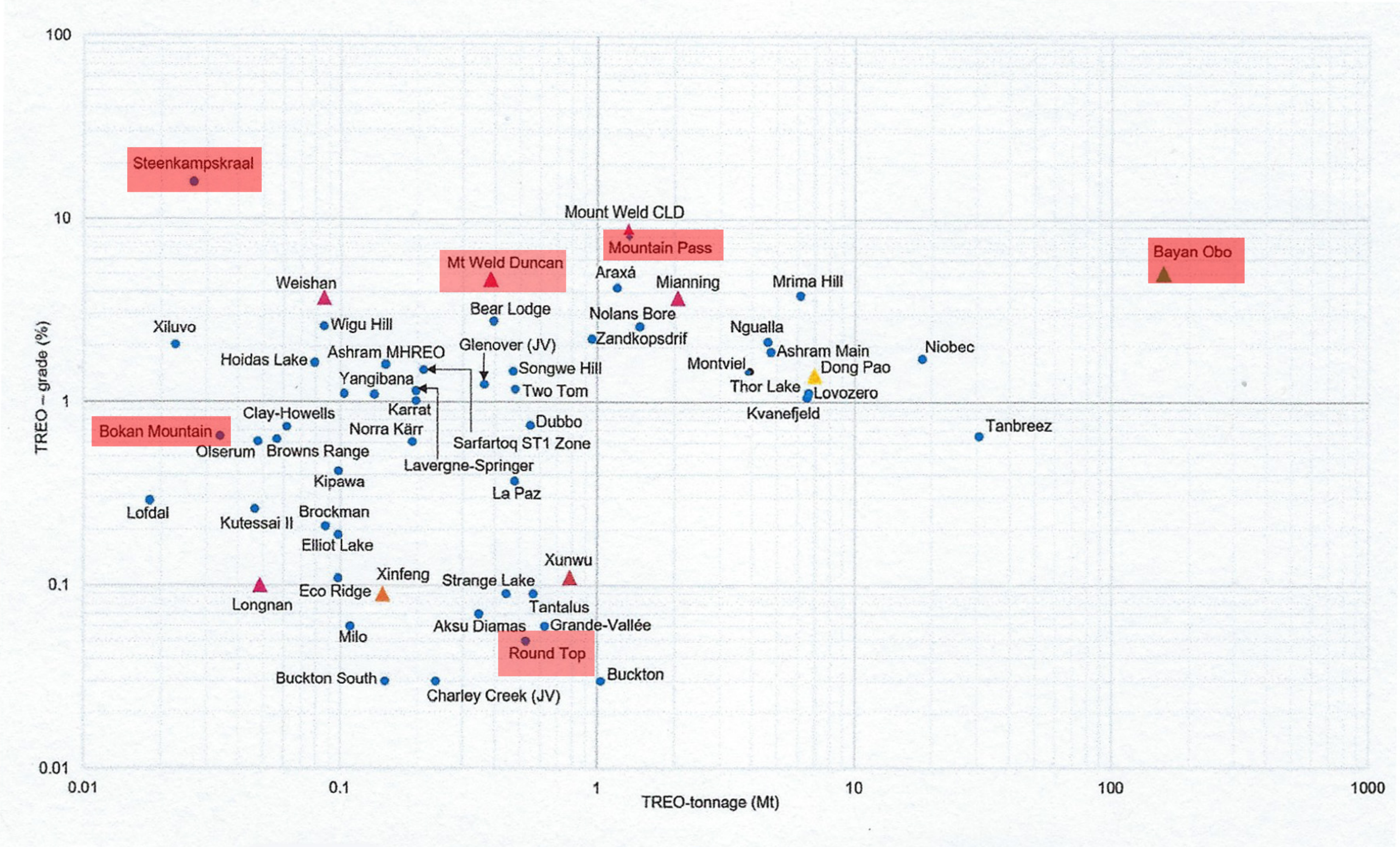


Source: USGS - Statistica

2013 2015 2017 2018* ** REE production coming China border? *** Bastnaesite, a rare-earth fluorocarbonate mineral, mined as a primary product at a mine in CA.

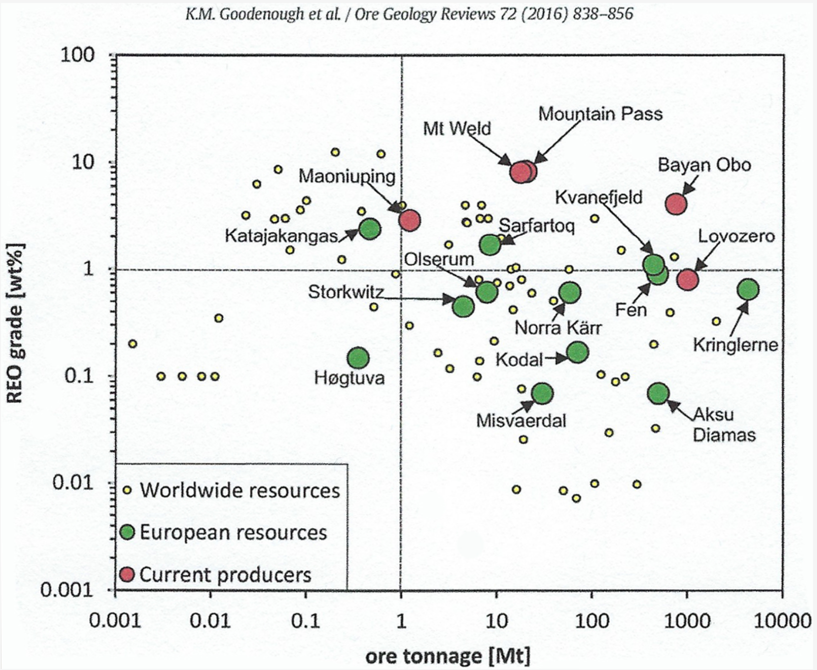
- ❖ World **REE** Mine Production – 2018: 170,000 tons to 210,000 tons **REO** in 2019,
- ❖ China produced ~ 71% and increasing, but illegal mining still exists,
- ❖ Vietnam has reported **REE** reserves located near the border with China,
- ❖ U.S. production from re-started Mountain Pass deposit, California 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.

REE Mines in Context with known G-T in REE Deposits



The ore grade and tonnage for advanced stage REE deposits.

Zhou, et al., ([2017](#))



- 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](#)).

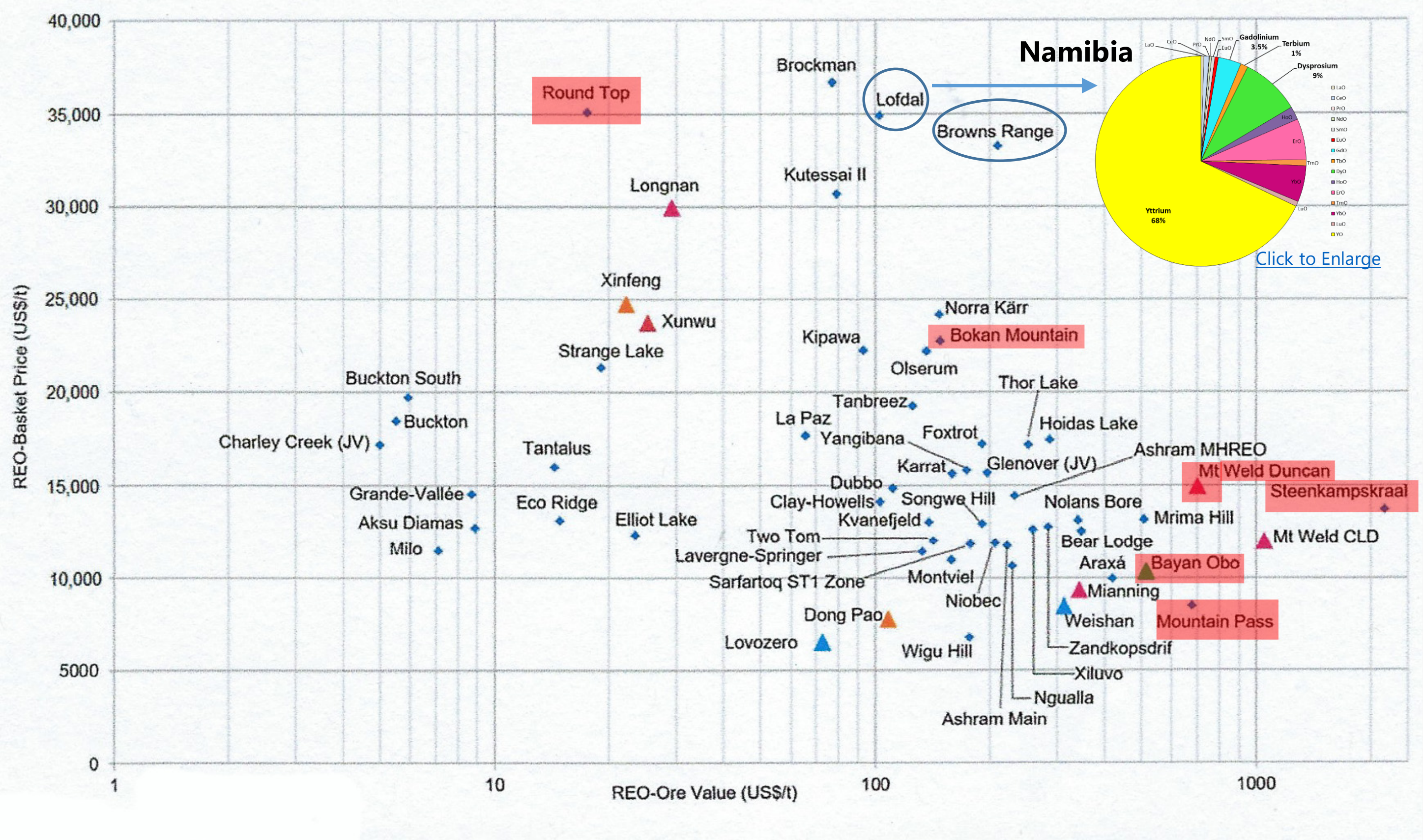
REE Use and Price Over Time

Rare-earth oxide industry uses and market prices.*

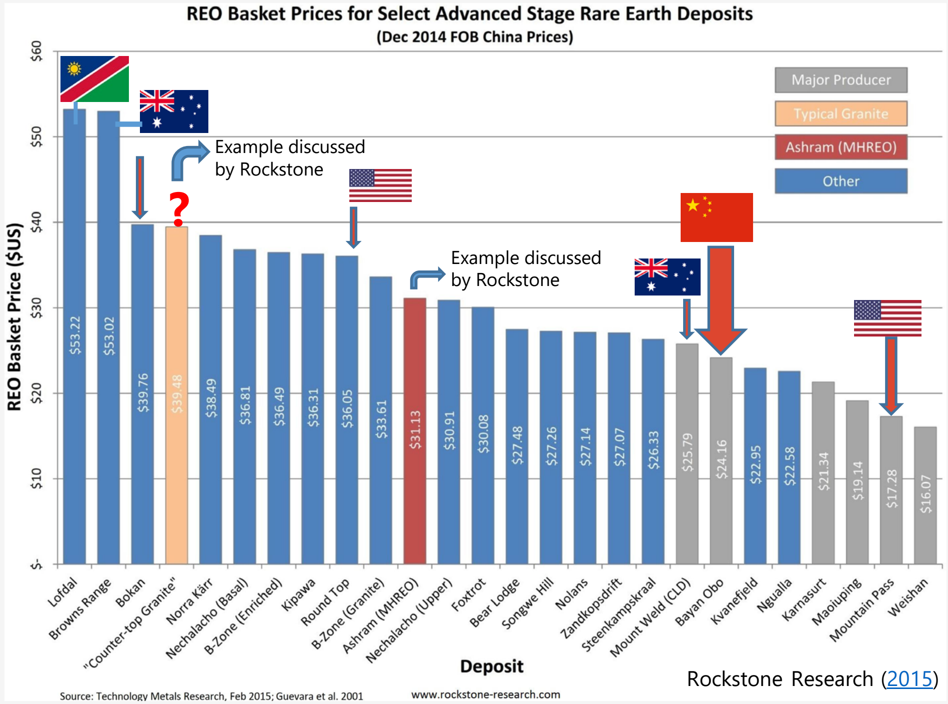
Metal Oxide	Principal Uses	Price US$/kg October, 2008	Price FOB China July, 2019			2020
Lanthanum oxide 99% min	Rechargeable batteries	8.50 –9.00	$ 1.68	↓	↑	$ 3.30
Cerium oxide 99% min	Catalysts, glass, polishing	4.70 –4.90	$ 1.90		~	$ 1.90
Praseodymium oxide 99% min	Magnets, glasses colorant	31.80–32.70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

*Source: Substantially modified from MetalPrices.com, October 2008. Prices for 2019 and 2020 from: Kaiser Research On-Line (2019)

REEO Prices and Ore Value: Changing Demands Creates Value



The ore value and basket price for advanced stage REE deposits. Zhou, et al., (2017)



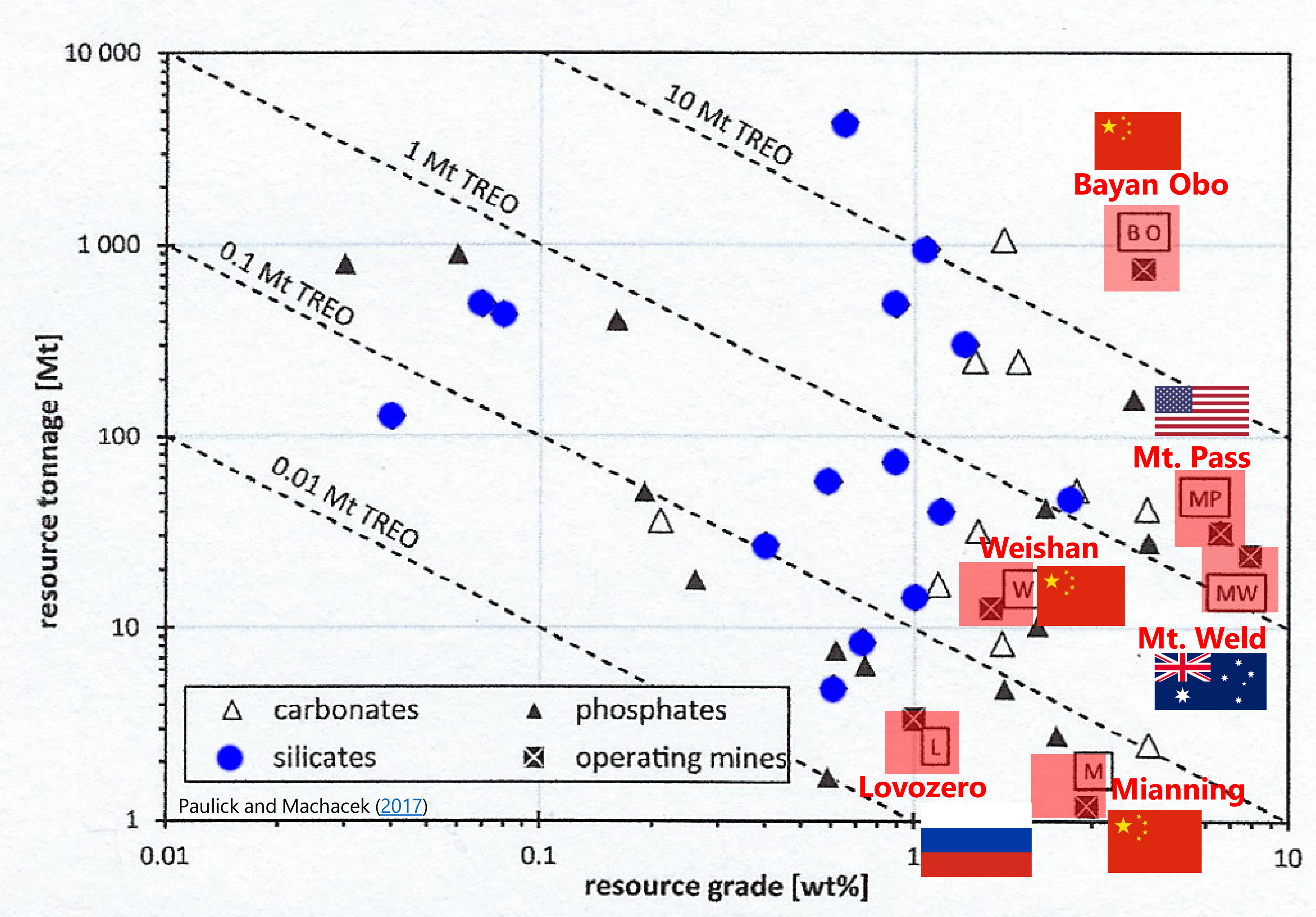
Rockstone Research (2015)

- During the initial **REE** "Bubble" in 2010 t0 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. and
7. Assumes standardized forms and specifications of final saleable REO products, not like gold w/ an established market.

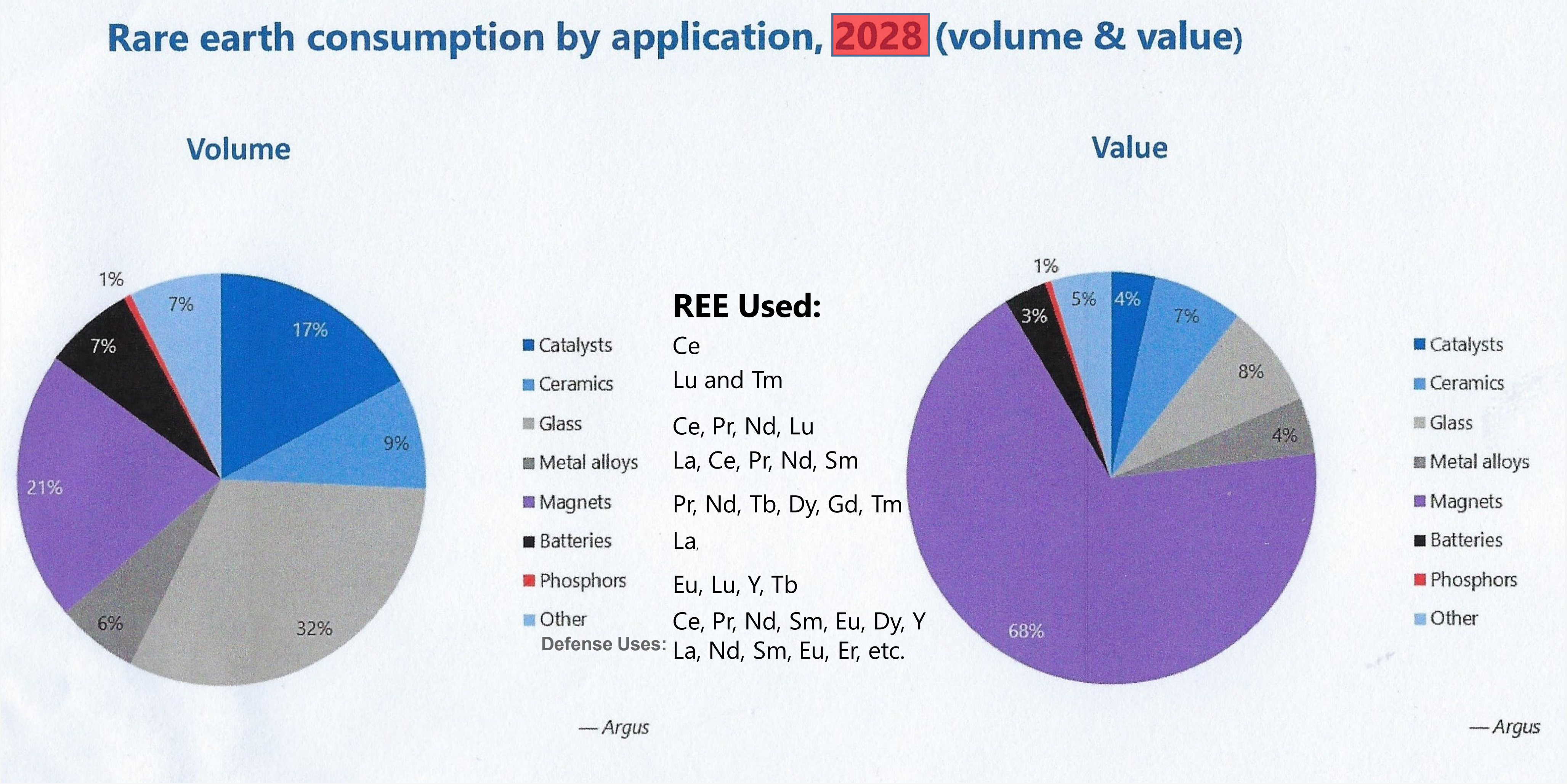
REE Resource Reserves and Ore Grades Make All The Difference in Economics



General Conclusions:

- **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**.

REE Future Use and Value



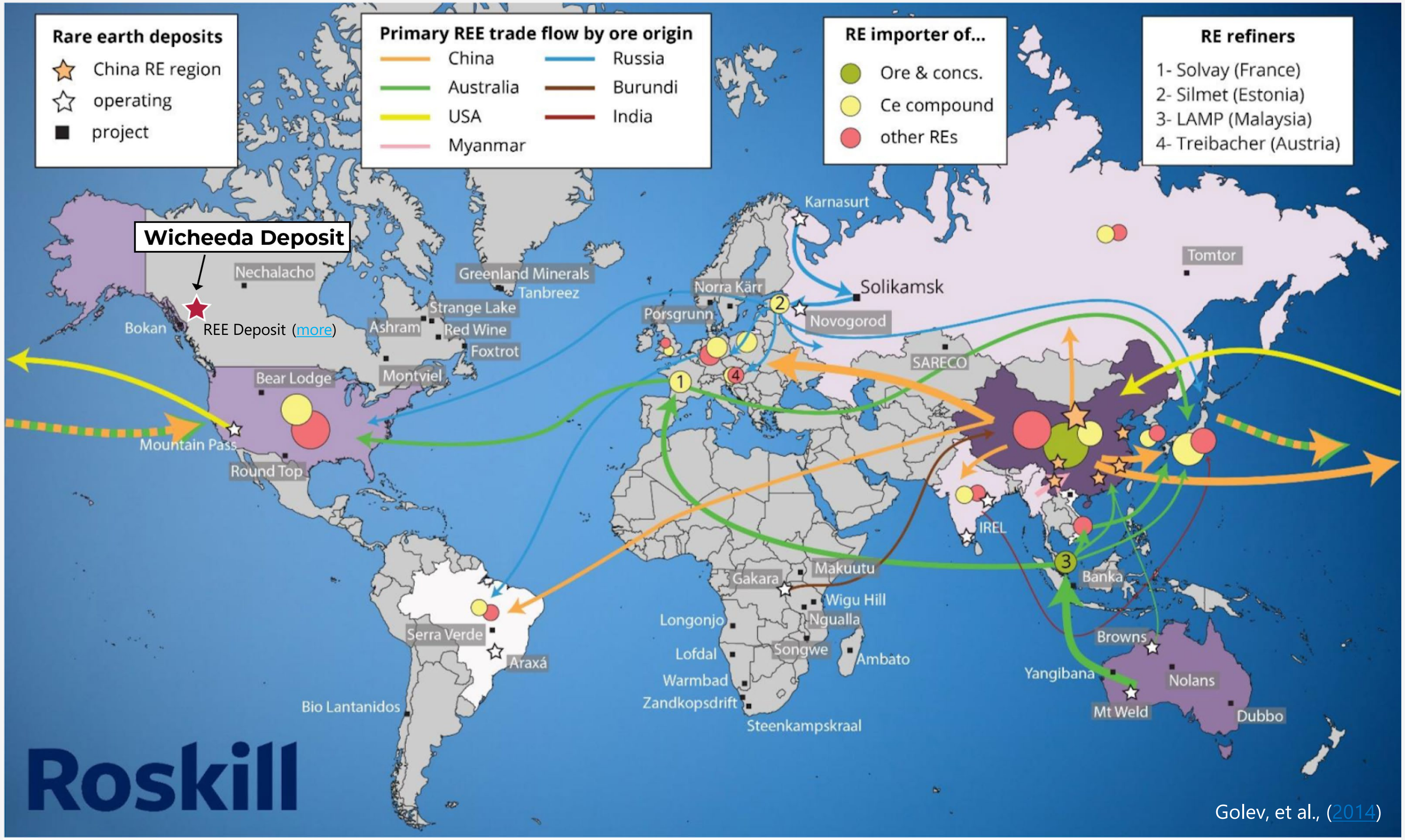
REE Used:

Catalysts	Ce
Ceramics	Lu and Tm
Glass	Ce, Pr, Nd, Lu
Metal alloys	La, Ce, Pr, Nd, Sm
Magnets	Pr, Nd, Tb, Dy, Gd, Tm
Batteries	La
Phosphors	Eu, Lu, Y, Tb
Other	Ce, Pr, Nd, Sm, Eu, Dy, Y
Defense Uses:	La, Nd, Sm, Eu, Er, etc.

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

Argus Research (2019)

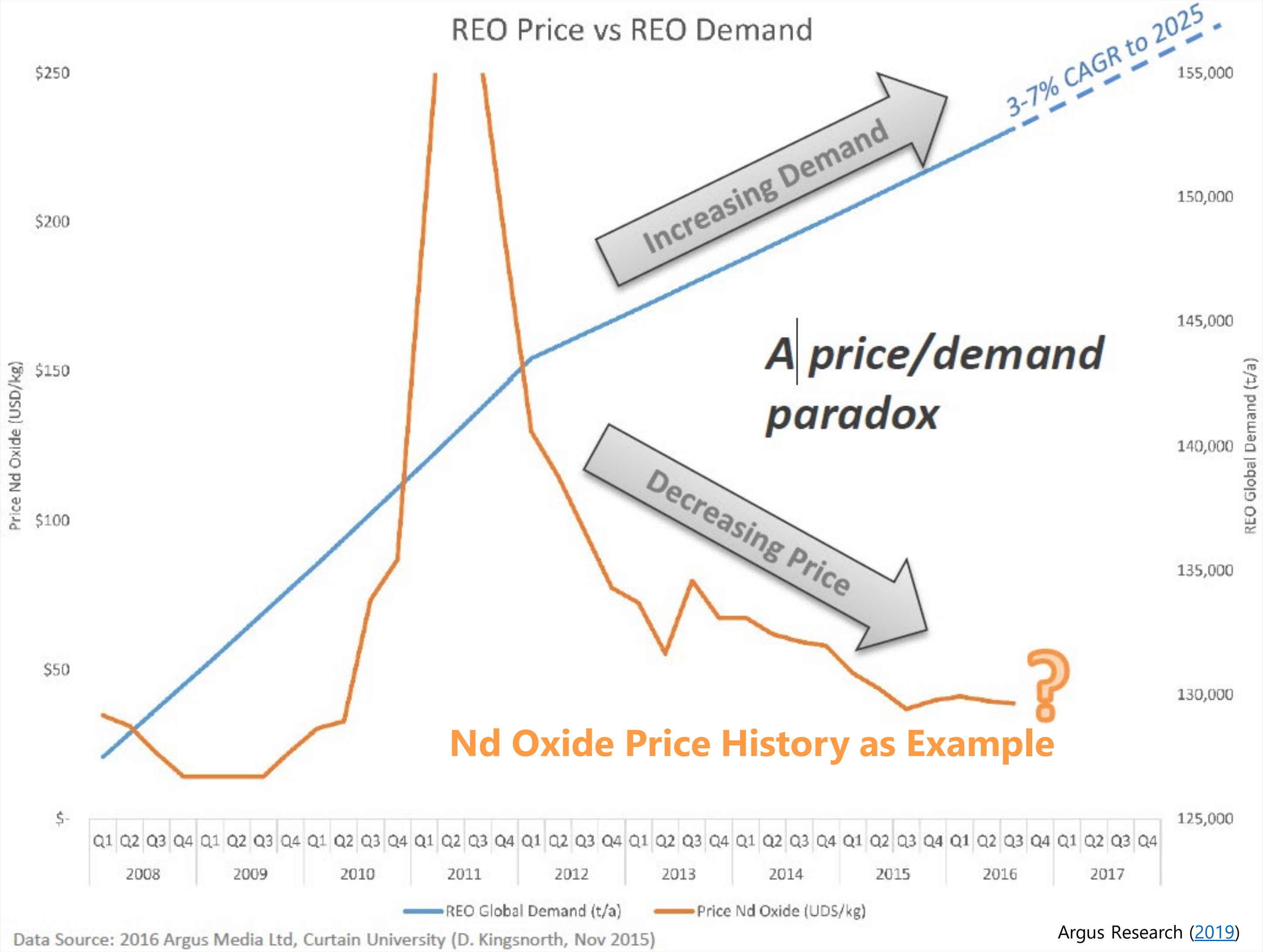
REE Historical Trade Routes: Major Sources, REE Refiners



Bottom line ….

- 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).

REE Price-Demand Complexities to Continue ….



Argus Research (2019)

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.

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